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R. J. Williams.

May – 1930

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DRAFT AND CAPACITY OF CHIMNEYS

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PREFACE

The chimney is one of the most important parts of a steam power plant yet very little information has been published on determining its proper size or investigating its draft and capacity performance. Until the last few years, most chimneys were proportioned by empirical equations which were deduced for specific cases and then used generally and indiscriminately. No thorough analysis was made of the draft and capacity requirements of the chimney installation taken as a unit. This method, approximate though it was, gave results which were sufficiently accurate perhaps for the small plant which was not subjected to any extraordinary conditions and which was ordinarily run at normal rating.

After the development of the large steam power plant, however, with its heavy requirements and its variable operating conditions, more accurate and extensive data and information on draft and capacity of chimneys were demanded. As the size of the plants increased, it became more difficult to determine accurately the proper size of chimney required and as a consequence more thought was given to this subject and designers and operators showed increasing interest in securing more reliable information. Most treatises on power plants contain a chapter on draft and chimneys which usually treats of these subjects in a general and elementary way and which, of necessity, must be brief. Also many articles in the technical magazines and trade catalogs have treated of special features of draft and capacity of chimneys. But no book has as yet appeared on draft and capacity of chimneys, treating of these two very important factors alone in a general and comprehensive manner.

This book, which is the result of a long experience in this line of work, is presented in an attempt to fill this need. The subject matter was published serially in COMBUSTION, a publication which is regarded as an authority, in 1924 and 1925. The aim and purpose throughout has been to review and assimilate the field of draft and capacity of chimneys, arrange the matter in logical order, and present the facts so that they may be applied to any condition of operation.

The subject matter has been developed primarily from a theoretical standpoint and then amplified by experimental data to conform with actual practice. Experimental data on performance of chimneys, however, is very meagre and there is great need of much work on this subject. Any new data will not in all probability affect results to an appreciable extent since the actual performance of chimneys accords well with theory.

Particular attention is invited to the fact that no attempt has been made to develop theory or interpret practice of power plant factors other than that of the subject in hand, but which of necessity must be included therewith, such as loss of draft through the boiler, loss of draft through the fuel bed, rate of combustion, and so on. Data and subject matter pertaining to these factors has been accepted at its face value and has been incorporated in the text as such. An effort has been made to clear up some of the erroneous ideas of the nature of draft, ideas which have materially hindered in a clear understanding of the subject and which doubtless have caused much harm and inconvenience in plant design and operation.

In developing the theory of draft and capacity, the two have been dissociated entirely; that is, it has been assumed that the height of the chimney is dependent only on the draft requirements and the diameter only on the capacity requirements, although each has a secondary influence on the other.

This book has been written for the designer of power plants who is desirous of investigating all of the conditions to which his contemplated chimney may be subjected to the end that the proper size may be attained, and for the operator of power plants who wishes to check the size of his existing chimney with the view of discovering draft and capacity shortcomings and eliminating them should there be any.

It is hoped that this book may be the beginning of what will ultimately be a larger and more extensive and comprehensive work. There is no element in a steam power plant of more importance than draft and capacity and no appliance of more consequence than the chimney. Therefore, in view of these facts, the author welcomes constructive criticism and helpful suggestions to the end that the usefulness of this book may be increased.

J. G. MINGLE

Indianapolis, Indiana
Nov. 2, 1925.

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Draft and Capacity of Chimneys

CHAPTER I

INTRODUCTION

Draft and Its Importance

In no field of commercial endeavor have greater strides been made during the past decade than in the field of steam power plant engineering. A steam power plant that was considered up-to-date and modern in every respect only ten years ago is now out-of-date or practically obsolete. The increasing demand for higher plant efficiency and cheaper steam has resulted in the development of many new accessories, such as economizers, feed water heaters, stokers, recording instruments, etc., all of which tend to relegate an old plant still further in the background. The size of the plants and plant units has increased enormously in late years. Some years ago, a five hundred horse-power boiler was considered a large unit while to-day fifteen hundred horse-power boilers, and even larger ones, are common. A twenty-five hundred kva. turbine was considered a large machine only a short time ago while at the present day several fifty-thousand kva. units are in operation. With the growing scarcity of good coal and its constantly increasing cost, cheaper grades of this commodity must be burned and, as a result, combustion problems are encountered which tax the ingenuity of the best engineers. Hand firing has been supplanted almost entirely by stoker firing. Remarkable results are being obtained in burning all kinds of coal with automatic stokers and the cheaper and poorer grades of coal are now being burned with high combustion efficiency. All of these new accessories and larger plant units tend towards the production of cheaper steam.

During the past few years another important problem in reference to combustion has come rapidly to the front, viz: smokeless combustion. This has been largely the result of civic agitation. There is scarcely a city of any importance in the country that has not effected at least some legislation against the "smoke evil." While much of the visible smoke in a city comes from house chimneys, yet it is a fact that some large plants produce a smoke nuisance that is extremely bad. Many people have an idea that smoke comes from burning a poor grade of coal and that the amount of smoke coming from a chimney is, in a degree, a measure of the quality of the coal. This is not strictly true for probably as much smoke comes from bad firing methods of a good quality of coal as comes from any other cause. There are several "smoke consumers" on the market but the best smoke consumer is an arrangement which will *prevent* smoke and this can be accomplished only by a high furnace, a good stoker and a tall chimney.

Cheaper steam and smokeless combustion at the present day are two of the most important problems in the further development of the modern steam power plant. Many kinds of new plant accessories are being sold and installed in new and old plants, the chief purpose of which is to increase the plant efficiency and cheapen the cost of steam, and also to eliminate the nuisances as much as possible. The best constructed and the most efficient accessories possible would be practically useless were it not for the one element that, above all others, determines and controls the overall efficiency of the entire steam power plant, and that element is *proper draft.*

Draft is and should be considered one of the most important factors in the design of a new steam power plant. Without draft, the plant would be useless of course. Without sufficient draft, the plant may, and usually does, show a relatively low efficiency. With an excess of draft, other troubles are encountered which are almost as bad as those caused by an insufficient draft. The efficiency of the plant may be traced directly to the intensity of the draft and it is doubtless true that fully sixty per cent of the troubles encountered in and around a steam power plant may be traced back to the lack of sufficient, or an oversupply of, draft.

In spite of the fact that draft has such an important influence on the operation of a plant, very little information on this extremely important subject has been published. This, no doubt, has been due to the lack of sufficient and reliable data, or its availability. Draft, even to the expert designer, oftentimes is approached as an element of mystery. Again, the subject is often considered analogous to hydraulics and assumptions and deductions made from the standpoint of liquids. The analogy holds true to a certain extent but a strict adherence to the principles of hydraulics may lead, and often does, to erroneous conclusions.

For some unaccountable reason, there seems to be a great deal of confusion and misconception in regard to the true nature and meaning of draft, especially natural draft. Some writers have defined draft as a wind or a current of air or gases blowing through the boiler, breeching and chimney. Such a definition is erroneous in the face of the facts. Draft is simply a difference in pressure, or a difference in head, between any point inside the boiler, breeching or chimney and the outside atmosphere. Draft is, in short, a *static force*. There is no element of motion inferred in reference to draft. Draft is not velocity and there is no direct connection between the two. The current of air or gases passing through the ashpit or air chamber entrance and then through the boiler, breeching and chimney is the direct result of draft or a difference in pressure.

Definition of Draft

Draft, in general, in a steam power plant may be defined as the difference in pressure between any point in the boiler, breeching or chimney through which the gases flow, and the atmosphere. It is, in a few words, the difference in pressure available for a flow of air or gases so that the gases which result from the union of air (oxygen) with the fuel may be successfully conducted past the obstructions in the boiler installation, through the breeching and finally through the chimney out into the upper regions where they will be least objectionable.

Production of Draft

Draft may be produced in two ways, viz:

1. By artificial or mechanical means,
2. By natural or thermal means.

There are then two kinds of draft according to the manner in which it is produced, viz:

1. Artificial draft,
2. Natural draft.

Artificial draft is produced by means of a fan, a blower, or a steam jet, and natural draft by means of a chimney and heat. It is with natural draft that the major portion of this book deals.

Draft, or difference in pressure, may be either above or below atmospheric pressure. As ordinarily used, however, the term *draft* represents a pressure below atmospheric pressure, or, in other words, there is a suction at the point under consideration. The term *plenum* is used to represent a a pressure above atmospheric pressure. A plenum can be produced only by a fan as in forced draft. A suction, the equivalent of natural draft, can be produced also by a fan as in induced draft.

Artificial Draft

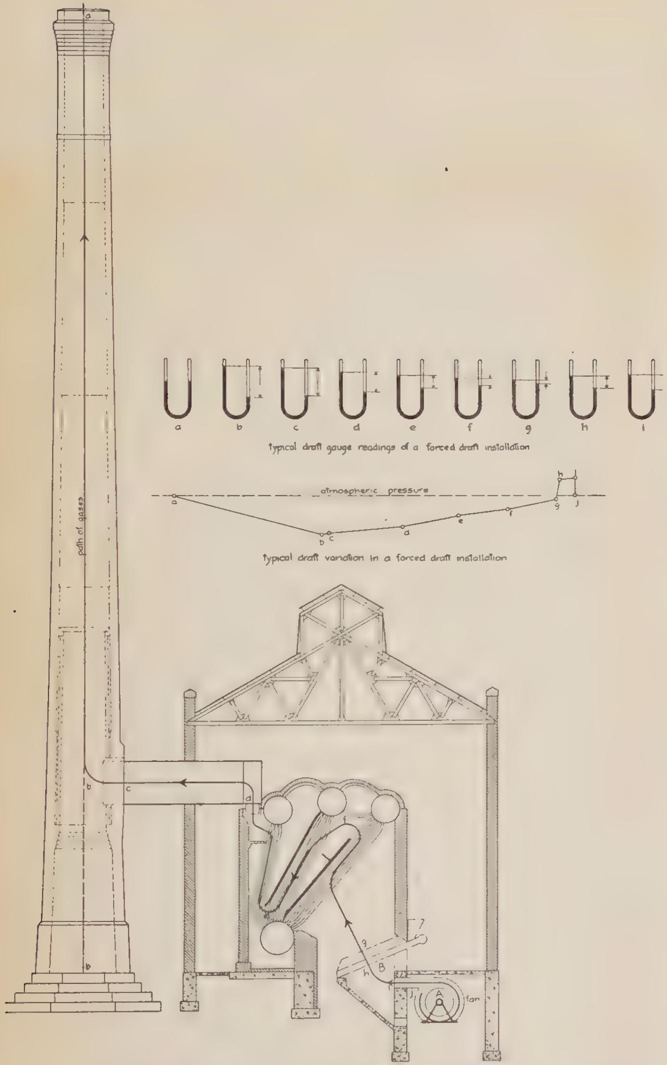
Artificial draft is of two kinds, viz:

1. Plenum or forced draft,
2. Vacuum or induced draft.

Artificial draft is used in installations where it is necessary to burn more coal in an existing plant or in connection with an existing chimney, and also where the conditions imposed on the plant require a more flexible arrangement than is possible with a chimney alone. Artificial draft arrangements are used mostly as auxiliaries to chimneys.

Forced Draft

Fig. 1 shows a diagrammatic section of a typical forced draft installation. The fan or blower *A* takes the air at atmospheric pressure and discharges it into a closed ash-pit or air-chamber *B* at a pressure considerably above atmospheric pressure. The air is then forced through the grates and fuel bed *C*, a plenum having been created below this part of the installation. This system is often used in old plants where it is desired to force the old boilers above their normal rating; in plants burning refuse or poor grades of coal or screenings, where an intense draft is required for efficient combustion; and in plants where an additional boiler is installed or where the boilers have been changed or increased in size and it is impossible to alter the chimney. Forced draft is also used with mechanical stokers. Quite often the air supply is preheated in a chamber built around the


a
b
c
d
e
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typical draft gauge readings of a forced draft installation
atmospheric pressure
typical draft variation in a forced draft installation
path of gases
A
B
fan

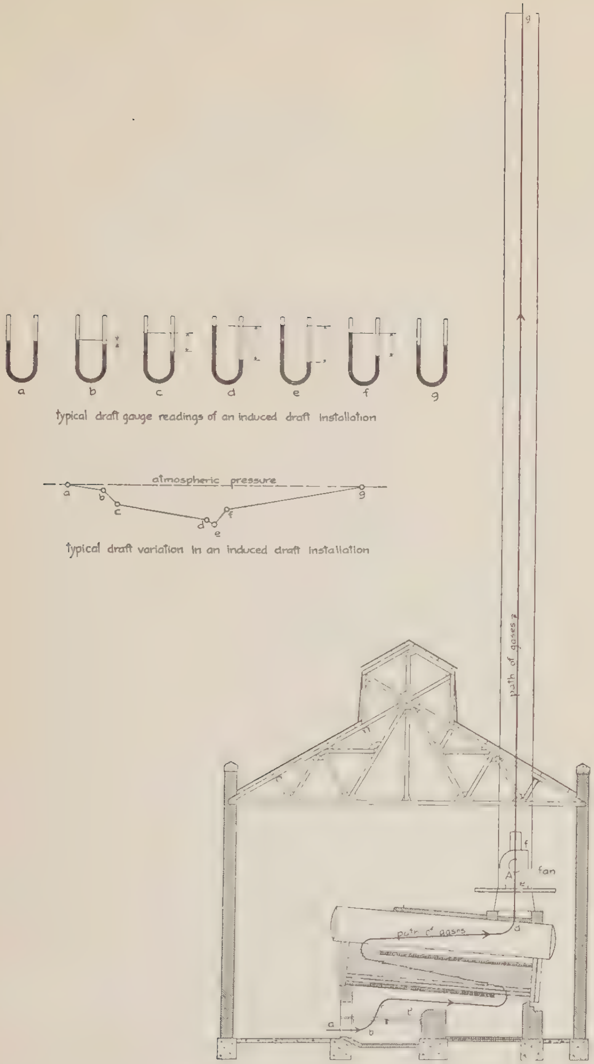
Fig. 1. Diagrammatic Section of a Typical Forced Draft Installation.

breeching, thereby effecting a higher temperature in the furnace. This has a tendency to cool the chimney gases and may decrease the draft produced by the chimney. The air supply may enter the air-chamber through the bridge wall from the rear, through an underground duct, or through the sides of the setting.

Chimneys are always used with forced draft installations. An ideal arrangement is to provide sufficient draft by means of fans to overcome the resistance through the grates and the fuel bed and then create sufficient suction or draft by means of a chimney to overcome the resistance through the boiler, breeching and chimney itself. Forced draft arrangements are not as frequently used as induced draft in new plants but are almost always used in increasing the capacity of old plants. The one disadvantage of forced draft is that the gases are forced out through the doors during firing or inspection due to the fact that the pressure in the furnace is usually considerably above atmospheric pressure. This objection can be overcome by placing a damper in the blow pipe and closing it during firing or inspection. In mechanical stoker installations, however, the pressure in the combustion chamber is usually slightly below atmospheric pressure and the objection is then entirely removed.

Induced Draft

Induced draft installations are by far the more common of the two artificial draft producing ar-


a
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typical draft gauge readings of an induced draft installation
atmospheric pressure
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typical draft variation in an induced draft installation
g
path of gases
f
fan
A
e
d
path of gases
c
a
b

Fig. 2. Diagrammatic Section of a Typical Induced Draft Installation.

rangements. Fig. 2 shows a diagrammatic section of a typical induced draft installation. A fan or blower *A* is usually mounted above or on top of the boiler and the air sucked or pulled through the fuel bed *B*. In other words a partial vacuum is created above the fuel bed and the air, in attempting to seek an equilibrium of pressure, is pulled through the fuel bed. The products of combustion are then exhausted through the chimney. Induced draft arrangements are used extensively in heating and lighting plants which have variable and high loads. Since hot gases are handled, the blower system must have a capacity much larger than a forced draft fan which handles only cold air. The pressure in the furnace is below atmospheric pressure, consequently the ash-pit can be cleaned without stopping the fans. This cannot be done in a forced draft system where the pressure in the furnace is above atmospheric pressure. Also the fires burn more evenly in an induced draft system. An induced draft installation costs more than a forced draft, due to the larger fan required. The cost of operation is about the same in either case.

The advantages claimed of artificial draft are:

1. Flexibility,
2. Readily affects various rates of combustion,
3. Is not influenced greatly by atmospheric, climatic, or weather conditions,
4. Ease of control,
5. Produces any percentage of overload without an excessive expenditure of heat.

The disadvantages of artificial draft are:

1. Maintenance and upkeep of fans or blowers,

2. Requires considerable power to run fans,
3. Necessary to have duplicate fans to insure dependability,
4. Fans require considerable room.

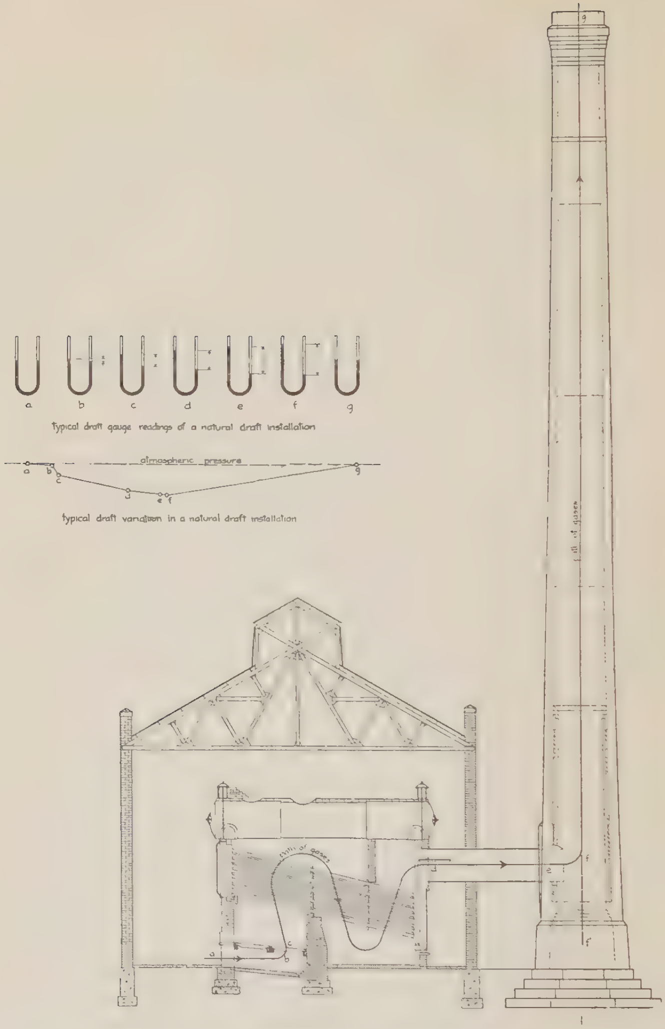
Balanced Draft

Balanced draft is a combination of forced draft and induced draft. Sufficient draft is provided by means of a fan to overcome the resistance or loss of draft through the grates and fuel bed, and the required amount of induced draft by means of a fan or a chimney, or both, to overcome the resistance through the boiler, breeching and chimney. The pressure between the two systems is mutually adjusted so that a practically atmospheric pressure, or a slight suction, exists in the combustion chamber. The control of the system is effected by:

1. The stoker speed,
2. The fan speed,
3. The damper.

The chief advantages claimed of balanced draft are that it:

1. Produces increased boiler and combustion efficiency,
2. Prevents escape of furnace gases through cracks and imperfect settings,
3. Reduces the air excess to a minimum,
4. Prevents stratification of air supply and gases,
5. Prevents a soaking up action of heat by the boiler brickwork by quickly removing the excess heat from the combustion chamber.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typical draft gauge readings of a natural draft installation
atmospheric pressure
typical draft variation in a natural draft installation
path of gases

Fig. 3. Diagrammatic Section of a Typical Draft Installation.

Natural Draft

Natural draft is the difference in pressure, or the difference in head, or the pressure head, or the pressure difference, produced by the difference in weight between the hot air or gases inside the chimney and an equal column of outside air. If one end of a glass U-tube, which is about half full of water, is connected to a chimney in which the air or gases are the same temperature as that of the outside air, the two columns of water will be at exactly the same level. If the air or gases inside the chimney be heated, the level of the water in the column of the U-tube attached to the chimney will be higher than the other. This indicates that there is a difference in pressure, that on the outside of the chimney being the greater. This difference in pressure will cause a flow of air into the ash-pit entrance, if the chimney be connected to a steam boiler. The incoming air in turn becomes heated and, having united with the fuel to form gases, rises and passes out through the chimney. This action becomes continuous and will be prolonged as long as the fuel lasts and there is a clear passage through the installation. One inch difference in the level of the two water columns corresponds very closely to a difference in pressure of 5.20 pounds per square foot.

Natural draft, then, is produced thermally by creating a difference in temperature between the gases inside the chimney and the outside air, thereby creating a difference in pressure which causes a flow or circulation. Natural draft is, in effect, a form of induced draft in that it causes the air to be supplied to the fuel bed by means of a suction.

Natural draft in chimneys is analogous to difference of head in water. The chimney may be regarded as a vertical pipe with a small opening at one side near the bottom. The outside air may be regarded as a fluid whose density is greater than that of the warmer air or gases inside the chimney. Hence, in attempting to approach an equilibrium which it never reaches, the cooler outside air continually flows towards the opening and into the chimney.

Natural draft, being a difference in pressure, is a static force and no element of motion is inferred when reference is made to it. Natural draft and velocity of the chimney gases should not be confounded, as there is no connection or relation between the two. As will be seen later on, the maximum static draft of a chimney will be obtained when the velocity of the chimney gases is zero and the gases are absolutely motionless. Motion, however, is produced as a *result* of natural draft as the gases are made to flow due to the unbalanced pressure.

Natural draft seems to be a difficult subject to comprehend and numerous analogies have been worked out to aid in a clear understanding of the manner in which it acts. The primary purpose of the chimney is a container in which to destroy equilibrium and thereby effect a difference in pressure which, in turn, causes the gases to flow.

Natural draft then, in short, is the difference in pressure as produced by a chimney and a difference in temperature available for the flow of gases.

The chimney may also be regarded as a vertical heat engine whose function is to pump air into the fuel bed and gases through the rest of the installation and then discharge them from its top.

In discussing the production of natural draft by a chimney, it is necessary to assume that the chimney is detached from the rest of the installation and that the gases inside the chimney are motionless. When the chimney is attached to the boiler and the gases are moving freely throughout the entire installation, the draft as produced by the chimney is "used up," or in other words there is a *loss of draft* or a decrease in pressure as readings are taken farther away from the chimney and towards the air entrance of the setting.

Natural draft as produced by a chimney is quite analogous to the head as produced by a tall standpipe, except that the action is reversed. The difference in pressure, or the draft, as produced by a chimney is due to the difference in weight between the warmer gases inside the chimney and an equal column of cooler outside air, and the direction of flow is from the outside to the inside. On the other hand, the difference in pressure, or head of the standpipe is due to the difference in weight between the water inside the standpipe and the outside air, but the direction of flow is from the inside to the outside. In each case, gravity is the actuating or impelling force, producing draft in the first case and head in the second. The head increases as the height of the chimney standpipe increases; and likewise the draft increases as the height of the chimney increases. Other factors such as density, temperature, friction, etc., will influence the intensity of natural draft and these will be discussed later on.

Natural draft may be considered as a form of either forced draft or induced draft, depending upon the point of view. If it is considered as a "push," then it is a form of forced draft, but if it is considered as a "pull," then it is a form of induced draft. The action of the chimney tends to create a vacuum throughout the installation and there is, therefore, a suction at every point, all of which are evidences of induced draft. The partial vacuum above the air chamber or ash-pit tends to suck in the air. If, on the other hand, it is assumed that the incoming air, being denser, pushes the warmer air upwards, natural draft may be classified as a form of forced draft. Forced draft, however, usually implies that there is a plenum below the grates and in this instance the comparison does not hold true. Continuing the argument further, the warmer gases inside the chimney, being considerably lighter in weight, ascend just as a balloon which is full of hot gases ascends, and cooler air rushes in to take the place of the warmer gases in an attempt to produce a state of equilibrium which is never reached as long as the installation is in operation. In the light of the above argument, then, natural draft is a "pull" and not a "push," or in other words the cooler air rushes in to supplant the warmer air or gases because the latter have risen of their own accord and not because the cooler air pushes the warmer gases upwards. Natural draft then is a form of induced draft in that the gases are "induced" to come forward. In the case of forced draft, the fan itself produces most of the difference in pressure, or draft, by destroying the equilibrium in a violent manner and the cooler air from the fan pushes the warmer gases through the installation, or at least the greater part of it, because there is a pressure back of them.

Much of the misunderstanding of the nature of natural draft doubtless comes from the use of such common expressions as "sitting in a draft," "closing the draft in a furnace," etc. Inasmuch as natural draft is a static force, such expressions are manifestly wrong. The direct *result* of draft, however it may be produced, is a current of air or gases as the case may be. Winds are currents of air and are the results of a draft on an immensely large scale. The warmer air next to the surface of the earth has a tendency to rise and the cooler air, being denser, descends and tends to supplant the former. This results in gigantic movements of air called winds. When we sit near an open window and the wind blows on us, we are not sitting in a draft but in a current of air or something which is the result of a draft. Again, in reference to the furnace, we do not shut off the draft but shut off the air supply and therefore throttle the circulation. As a matter of fact the draft is greater when the air inlets are closed than when they are open, due to the fact that there is no circulation of gases and therefore no friction. The result of natural draft when there is an air inlet at the bottom of the chimney is a current of gases going up the chimney. It is this current of gases that is often mistaken for draft. This current of gases determines the capacity of the chimney and has nothing to do with the production of draft.

Natural draft, like other forms of draft, is measured in terms of inches of water. For instance, when it is stated that there is a draft of one inch of water at a certain point in the installation, it is meant that there is a difference in pressure sufficient to support a vertical column of water one inch high. One inch difference in height between the two water columns in a U-tube corresponds closely to a difference in pressure of 5.2 pounds per square foot. The pressure at the bottom of a stand-pipe is measured by a gauge measuring pounds per square inch. Natural draft also could be measured in the same manner and in the same unit but it would require a very sensitive gauge to indicate the slight changes in pressure and, therefore, for convenience the measurement of draft is made in terms of inches of water which is both very practicable and accurate.

Fig. 3 shows a typical natural draft installation.

The advantages of natural draft are:

1. Absolute dependability,
2. No maintenance,

3. Chimney is everlasting,
4. Ordinarily no space required in boiler room,
5. Original low cost.

The disadvantages of natural draft are:

1. Relatively large chimney is required for peak loads,
2. When large chimney is built, excessive draft must be throttled,
3. Lack of flexibility,
4. Difficult to increase draft by adding to height of chimney.

The Chimney and Its Relation to Natural Draft

Chimneys in connection with steam power plants are required, in general, for two purposes, viz:

1. To help produce or create a draft,
2. To carry away and discharge the burned gases at an elevation which will make them least objectionable.

The height of the chimney determines the intensity of the draft and the diameter or area affects the volume of gases it can carry away. In any installation, the height of the chimney is determined by the draft requirements and the diameter by the volume of gases resulting from the combustion of the fuel. In determining the height and diameter of a chimney, it is necessary to dissociate the two completely and assume that the height of the chimney is dependent only on the required draft and the diameter only on the volume of gases handled. Each, however, has an indirect influence on the other, particularly the diameter on the height, which will be discussed later on.

Many erroneous theories have been advanced regarding the proper height and diameter of a chimney to satisfy certain requirements of a steam power plant, the most important of which is that for any certain set of assumed or actual operating conditions there are several sizes of a chimney which will answer the purpose and that it is necessary to determine the relative cost of all in order to arrive at the most economical size. This theory is wrong and is not borne out in practice. For any one set of operating conditions, assumed or actual, of a steam power plant there is one and only one size of a chimney which will answer the purpose. The height of the chimney is dependent primarily upon the assumed or required draft conditions and the diameter or capacity primarily upon the volume of gases necessary to be discharged, both based on the same operating conditions. Both the diameter and the height of the chimney may be determined directly from equations. It is true that the height of a chimney is influenced somewhat by the diameter, especially that portion of the height necessary to overcome the loss of draft due to friction within the chimney. Likewise the diameter is dependent to a certain extent upon the height of the chimney. In most cases it is not possible to arrive at the correct height and diameter with one substitution in the equations, and after a trial size has been found it may be necessary to make a couple of slight changes in each in order to satisfy perfectly the theoretical requirements. But in no case is this to be construed by implication, or otherwise, that there are several combinations of heights and diameters which will answer the purpose. This theory has been the cause of an endless amount of trouble with draft problems in a steam power plant. When a chimney has been found to be too short and an addition to it has been made, it is the draft principally that will be affected. In order to secure more draft then, with an existing chimney, it is necessary to increase the height. In order to secure more capacity, it is necessary to increase the diameter or increase the velocity of the chimney gases. Increasing the height of the chimney increases the velocity of the chimney gases to a small extent, which may be sufficient for the purpose in a small plant but under average conditions the increase in the velocity is only a small percentage of the actual amount required.

Another misconception commonly encountered is that maximum draft refers to the maximum volume or weight of chimney gases moved in a chimney. This idea also is erroneous. Maximum draft is the maximum difference in pressure and is dependent upon the temperature of the chimney gases and the height of the chimney, while the maximum capacity is the total amount of gases a chimney is capable of moving and is dependent upon the temperature of the chimney gases and also upon the amount of air admitted for combustion. The draft of a chimney increases as long as the temperature of the chimney gases increases but the capacity of a chimney increases as the temperature of the chimney gases increases only up to about 600 degrees Fahr., after which the capacity actually decreases as the temperature of the chimney gases increases. As a matter of fact, the maximum draft of a chimney is obtained when the complete installation is practically air-tight and no air is admitted to the fire. In this case there would be no movement of gases because, since no air was admitted, there would be nothing to move and the actual capacity would be zero. On the other hand, if the boilers are run at their maximum rated capacity, the loss of draft through the boilers would be at a maximum, the velocity of the gases doubtless would be at the maximum, and the maximum *available* draft as produced by the chimney would be greatly reduced, but the capacity of the chimney would be at its maximum.

In a steam power plant it is of paramount importance that the chimney be of sufficient size to accommodate the installation when it is run at its maximum capacity. If the chimney is too short, there will be insufficient draft, the fires in the boilers will be smoky and sluggish and eventually may go out, the boilers cannot be operated at even their normal rating, and the temperature of the chimney gases may be relatively low, thereby reducing the capacity as well as the draft. If the chimney is too high, there will be an excess of draft, the fires will burn out quickly in spots, much fuel will be consumed and some wasted, and the chimney gas temperature may be excessively high, thereby, furthermore, increasing the draft on the one hand and decreasing the capacity on the other. Of the two adverse conditions, it would be better to have the chimney too high, for in this case the draft can be controlled by a damper, whereas if the chimney is too short, it would be necessary to create more draft by resorting to a fan or by adding to the height of the chimney.

If the diameter of the chimney is too small, the capacity of course will be reduced, there will be a back pressure due to the constricted area, the velocity of the chimney gases will be greatly increased thereby decreasing the available draft, excessively high temperatures will develop in the combustion chamber, thereby damaging the refractory brickwork, and the gases may become stratified in the combustion chamber and also in the boiler. If the diameter is too large, the velocity of the chimney gases will be relatively low, the temperature of the chimney gases may be relatively low or the temperature of these gases may drop rapidly during their passage up the chimney due to the comparatively long time they are inside the chimney, and again stratification of gases in the combustion chamber may result due to the low velocity of the gases in the chimney and the fact that they are not taken away quickly. Of the two adverse conditions, it would be better to have the chimney too large in diameter as in case of extreme emergency the velocity of the chimney gases may be increased by a fan, whereas if the diameter is too small, the situation is about hopeless.

It is extremely poor economy and bad engineering practice to attempt to increase the capacity of an existing chimney by adding to its height. Adding to the height of an existing chimney will always increase the draft and also will increase the velocity of the chimney gases, due to the increased head, just as an increase in the height of a standpipe will increase the head and also the velocity of the issuing jet. Therefore, the capacity of the chimney will be increased due to the greater amount of gases expelled during a given interval of time. But, as a general rule, the increased capacity, due to the increased velocity, is only a small part of the increased capacity required. Unsurmountable construction difficulties quite often are encountered when an attempt is made to add brickwork on top of an old chimney structure. Practically all masonry chimneys are tapered and in order to present a good appearance it would be necessary to make the taper of the new part, or extension, the same as that of the old structure; but this very act would defeat the purpose of the extension inasmuch as tapering the new part would of necessity decrease the inside diameter of the chimney. Of course the walls of the extension could be built vertical as is quite often done but this gives the whole chimney an unsightly appearance. Again, all masonry chimneys are designed as a unit and the wall thickness and section length at the top is a minimum in the majority of cases. Adding to the height of the chimney then would decrease the stability of the chimney throughout and increase the stresses in the shaft towards the bottom of the shaft. A chimney is similar to any other masonry structure in that it is subject to the same limitations as to design and usage after construction.

Importance of Draft

Very few engineers realize the great importance of draft in a steam power plant installation, whether it be mechanical or natural draft. The increasing demand and tendency to operate boilers at high overloads, the increasing practice of burning poorer grades of coal, and the increasing demand and use of stoker-fired installations have imposed conditions on the operation of a plant that requires great flexibility, especially in regard to draft. Since an average plant is built by several different contractors and the plant accessories are furnished by several different manufacturers, there is often some lack of correlation in spite of the best superintendence and inspection, and imperfections and mistakes often creep in during construction. The design of the plant has been made from a theoretical standpoint and amplified more or less to conform with field practice. Improper design or faulty construction in one or more parts may nullify the workings or reduce the efficiency of the other parts or even the whole plant. Often wrong assumptions may have been made and also working units may be greatly in excess of those assumed. All of these adverse conditions tend towards a decreased plant efficiency. If the draft conditions in a plant are good, a multitude of adverse conditions that might otherwise cause trouble can be successfully handled. The designing engineer who makes absolutely sure that there will be ample draft in his proposed installation has every prospect of having a successful and efficient plant in spite of mistakes that may be made in design or during construction.

Natural draft and capacity data and calculations which are to be dealt with in detail in the succeeding chapters have for their ultimate object the determination of the proper size of chimney required in connection with a steam power plant.

CHAPTER II

THEORY OF NATURAL DRAFT

Definitions

Natural draft, as stated heretofore, is the difference in pressure caused by the difference in weight between the warmer gases within the chimney and an equal column of outside air.

For convenience, natural draft, which is an all-inclusive term, is sub-divided into three separate and distinct divisions, each of which has its own meaning, viz:

1. Theoretical draft,
2. Available draft,
3. Required draft.

The *theoretical* draft, commonly called the maximum theoretical static draft, is purely a theoretical quantity and cannot be measured accurately by a measuring device. It is the maximum difference in pressure when the chimney gases are stationary and there is no flow or circulation within the chimney, when the chimney gas temperature is at its maximum, and when the chimney itself is at its maximum height.

The *available* draft is the difference in pressure as measured or indicated by a draft gauge when the chimney, or plant, is in operation and the chimney gases are flowing freely. It is, in short, the theoretical draft less the amounts lost by the velocity of the chimney gases and also by the friction of the chimney gases on the interior walls of the chimney.

The *required* draft is the sum of the draft losses through the fuel bed, boiler, turns and breeching, or the sum of the balancing members of the natural draft equation. Arithmetically the required draft is equal to the available draft, but it is made up of different terms.

These three terms form the basis of the development of the theory of natural draft and the natural draft equation, and each will be explained and developed in detail in the following text.

Heat

Since heat is the source of energy for the production of natural draft of a chimney and also an important factor in determining its capacity, a short review of the manner in which it affects gases will be given.

Heat is matter in motion, or the motion of the molecules in a body. Upon the application of heat to a solid body, the increased velocity probably sets up a vibration which becomes so violent that the adhesion between the molecules becomes less and the body is changed into a liquid. If still more heat is applied or added, the molecules may become dissociated entirely and the liquid is then changed into a gas. Gases themselves expand when heated, and this expansion is due to the increased velocity of the molecules which forces them still farther apart. As a result the volume is increased. The phenomena of heat may be considered as a form of kinetic energy.

Temperature

Temperature is a measurement of the intensity of heat, or the measurement of the velocity of the vibrating molecules, or the rapidity of motion of the molecules. In general, when the molecules move slowly the temperature is relatively low, and when they move rapidly the temperature is relatively high.

The difference in temperature between two bodies is determined by the rate of transmission of heat from one body to another.

Temperatures are ordinarily measured in two scales, viz:

1. Fahrenheit scale,
2. Centigrade scale.

In the Fahrenheit scale, at present the more commonly used of the two, the freezing point is taken at 32 degrees and the boiling point at 212 degrees, the distance between the two being divided into 180 equal parts. In the Centigrade scale, the freezing point is denoted by 0 degrees and the boiling point by 100 degrees, the intervening distance being divided into 100 equal parts. The conversion from one scale to another is made as follows:

$$t_C = 0.5555\ (t_F - 32), \qquad 1$$

$$t_F = 1.8\ t_C + 32, \qquad 2$$

in which

t_C = temperature in Centigrade scale,
t_F = temperature in Fahrenheit scale.

Unit of heat

The unit of heat is called the British Thermal Unit, B.t.u., and is defined as the amount of heat required to raise the temperature of one pound of water from 39 degrees to 40 degrees Fahr.

Transmission of heat

Heat may be transmitted in three ways, viz:

1. Radiation,
2. Conduction,
3. Convection.

Heat that passes from one body to another by waves, similar to light waves, is transmitted by radiation.

Heat that is transmitted through the body itself, or from one body to another by direct contact, is transmitted by conduction.

When air or gases come in contact with a hot body, the former is heated and the heat is carried away. This is called transmission by convection.

Absolute temperature

When dealing with temperatures it is necessary to have some standard absolute method of comparison. In the expansion and contraction of gases.

it has been found that a perfect gas will increase or decrease 1/491.6 of its volume for each increase or decrease of 1 degree Fahr. in its temperature. At 491.6 degrees Fahr. below freezing or 459.6 degrees Fahr. below zero, therefore, the volume of the gas theoretically will be zero and the gas will disappear. This law holds true for all temperatures encountered in steam power plant work and for the purpose of comparison may be assumed to hold true for all temperatures. As a result of this law, an imaginary arbitrary temperature scale, called the absolute scale, has been devised and temperatures expressed in this scale are known as absolute temperatures. According to the absolute scale, the zero is 491.6 degrees Fahr. below freezing or 459.6 degrees Fahr. below zero on the Fahrenheit scale. Fahrenheit temperature readings are changed to absolute readings by adding 459.6 to the former. This scale is very convenient in that under constant pressure the volume of a gas is directly proportional to the absolute temperature.

Law of perfect gases

There are two well-known laws expressing the relation of pressure, volume and temperature in a perfect gas.

1. Boyle's law. At a constant temperature, the volume of a gas is inversely proportional to the pressure it supports, or, the density of a gas at a constant temperature is proportional to the pressure.

$$P_oQ = \text{a constant} \qquad 3$$

in which

P_o = atmospheric pressure
Q = volume of gas.

2. Charles' law. Under constant pressure, the volume of a gas is proportional to its absolute temperature, or, the pressure exerted by a gas whose volume is kept constant is proportional to the absolute temperature.

$$\frac{P_o}{P'_o} = \frac{T_c}{T'_c} \qquad 4$$

in which

P_o = initial pressure
P'_o = final pressure
T_c = initial absolute temperature
T'_c = final absolute temperature

Equation of a perfect gas

The equation of a perfect gas is obtained by combining Boyle's and Charles' law. From Boyle's law, if the pressure P_o is changed to P_1, and the volume Q to Q', the temperature T_c remaining constant,

$$\frac{P_1}{P_o} = \frac{Q}{Q'} \text{ or } P_1 = \frac{P_oQ}{Q'} \qquad 5$$

From Charles' law, if the temperature T_c is changed to T'_c and the pressure P'_o to P_1 the volume Q' remaining constant,

$$\frac{P_1}{P'_o} = \frac{T_c}{T'_c} \text{ or } P_1 = \frac{P'_oT_c}{T'_c} \qquad 6$$

Combining equations 5 and 6,

$$\frac{P_oQ}{Q'} = \frac{P'_oT_c}{T'_c} \text{ or } \frac{P_oQ}{T_c} = \frac{P'_oQ'}{T'_c}$$

But $\frac{P'_o Q'}{T'_c}$ is a constant which may be denoted by R.

Therefore for one pound of gas:

$$P_oQ = RT_c \qquad 7$$

and for W_a pounds of gas:

$$P_oQ = W_aRT_c \qquad 8$$

The value of R for dry air, under a pressure of 14.7 pounds per square inch and a temperature of 32 degrees Fahr., is equal to

$$R = \frac{P_o Q}{T_c} = \frac{14.7 \times 144 \times 12.39}{459.6 + 32} = 53.35$$

Therefore, for one pound of air with the units taken:

$$P_oQ = 53.35\ T_c \qquad 9$$

and for W_a pounds:

$$P_oQ = 53.35\ W_aT_c \qquad 10$$

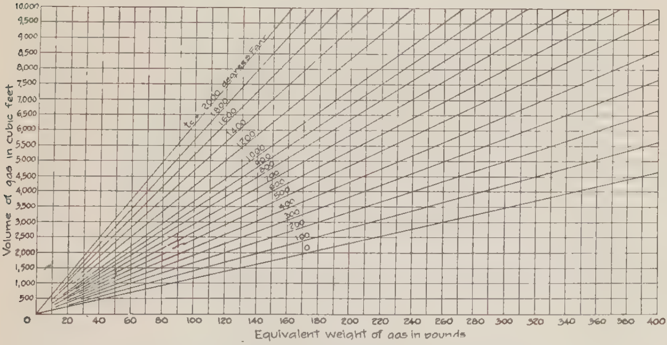

Fig. 4. Relation Between Volume and Weight of a Perfect Gas at Various Temperatures. Based on $P_o = P = 14.7$ pounds per square inch and $R = 53.35$

Equation 8 is the basis of all the theory leading to the derivation of the theoretical draft equation. It will also be found useful later in transferring the volume of a gas to its equivalent weight, and vice versa. Fig. 4 shows the relation between volume and weight of dry air for various temperatures, as noted.

$$\text{In general } R = \frac{P_o Q}{T_c} = \frac{P}{TW_c} \qquad 11$$

Fig. 5 gives the value of R for various values of W_c, based on $P_o = P = 2116.8$ lbs. per sq.ft., and $T_c = 32 + 459.6 = 491.6$ degrees Fahr.

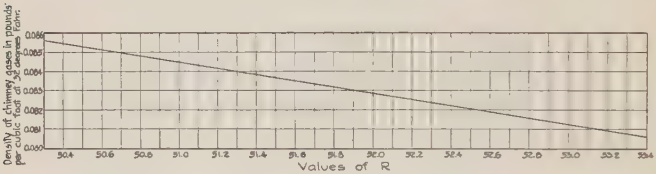

Fig. 5. Values of R in equation $R = \frac{P_o}{T_c W_c}$

Based on $P_o = P = 2116.8$ lbs. per sq. ft. and $T_c = 32 + 459.6 = 491.6$ degrees Fahr.

Intensity of theoretical natural draft

By intensity of theoretical natural draft is meant the degree of difference in pressure between the warmer gases within the chimney and the outside air when the gases are absolutely motionless. From equation 9:

$$Q = \frac{53.35\ W_a\ T_c}{P_o}$$

Then for one pound of air at standard atmospheric pressure and 32 degrees Fahr.,

$$Q = \frac{53.35 \times 1 \times 491.6}{14.7 \times 144}$$
$$= 12.39 \text{ cubic feet per pound,}$$

and the density is equal to

$$W_{o} = \frac{1}{12.39} = 0.08071.$$

Assuming, for illustration, an outside air temperature of 60 degrees Fahr. and a chimney gas temperature of 600 degrees Fahr. and neglecting, for the moment, the difference in density between the two, the intensity of theoretical draft is found as follows:

Under standard atmospheric pressure, the weight of a cubic foot of air at 60 degrees Fahr. is equal to

$$0.08071 \; \frac{491.6}{519.6} = 0.07636 \text{ pounds,}$$

and the weight of a cubic foot of chimney gases at 600 degrees Fahr. is equal to

$$0.08071 \; \frac{491.6}{1059.6} = 0.03745 \text{ pounds.}$$

Then the difference between the two weights is equal to

$$0.07636 - 0.03745 = 0.03891 \text{ pounds.}$$

For a chimney 100 feet high, for example, the difference in pressure would be equal to

$$0.03891 \times 100 = 3.891 \text{ pounds per square foot,}$$

or, in other words, if a chimney 100 feet high were suspended in the air and some kind of a diaphragm was stretched across its bottom, the pressure on the under side of the diaphragm would be 3.891 pounds per square foot.

Since a cubic foot of water at 60 degrees Fahr. weighs 62.366 pounds, an inch of water will exert a pressure of

$$\frac{62.366}{12} = 5.2 \text{ pounds per square foot.}$$

Whence the above pressure expressed in pounds per square foot is equal to

$$\frac{3.891}{5.2} = 0.7483 \text{ inches of water.}$$

Draft is measured in terms of inches of water for convenience. The simplest draft indicating instrument is the U-tube gauge, one end of which is attached to the chimney and the other left open to the air. A difference of one inch between the level of the two water columns of the gauge corresponds to a difference in pressure between the air and the chimney gases of 5.2 pounds per square foot.

There are five factors which influence the intensity of theoretical natural draft, viz:

1. Temperature of chimney gases,
2. Temperature of outside air,
3. Density of chimney gases,
4. Height of chimney,
5. Elevation of chimney above sea level.

In the above, if the chimney gas temperature is increased the difference between the weights of the two columns of gas and air becomes greater and the draft is increased. When the outside air temperature increases, the difference between the two weights becomes less and the draft is decreased. If the density of the chimney gases is increased, the difference between the two weights becomes less and the draft is decreased. When the height of the chimney is increased, the difference in pressure becomes greater and the draft is increased. Finally, if the altitude is increased, the density of the outside air and the chimney gases becomes proportionately less, the difference in weight becomes less and the draft is decreased. The above statements are based on the fact that all of the other factors remain constant,. while the one under discussion is being increased. There are many other conditions which affect the intensity of the draft, at times to a considerable extent, but which cannot be expressed in numerical quantities. As a rule they tend to neutralize one another, however, and, except in isolated instances, need not be considered at all.

General equation for the intensity of theoretical natural draft

The general equation for the theoretical draft is developed as follows:

The density of the outside air is equal to

$$d_o = W_o \frac{P_o}{P} \frac{T}{T_o} \qquad 12$$

in which

d_o = density of the outside air in pounds per cubic foot,
W_o = weight in pounds per cubic foot of dry outside air at 32 degrees Fahr. and standard, or sea level, atmospheric pressure,
P_o = observed atmospheric pressure in pounds per square inch,

P = standard, or sea level, atmospheric pressure in pounds per square inch,
T = absolute temperature of the outside air at 32 degrees Fahr. and standard atmospheric pressure,
T_o = absolute temperature of the outside air in degrees Fahr.,
= $t_o + 459.6$, in which t_o is the observed temperature of the outside air in degrees Fahr.

Table 1 gives the density of dry air at various temperatures. Fig. 6 shows the variation in the density graphically.

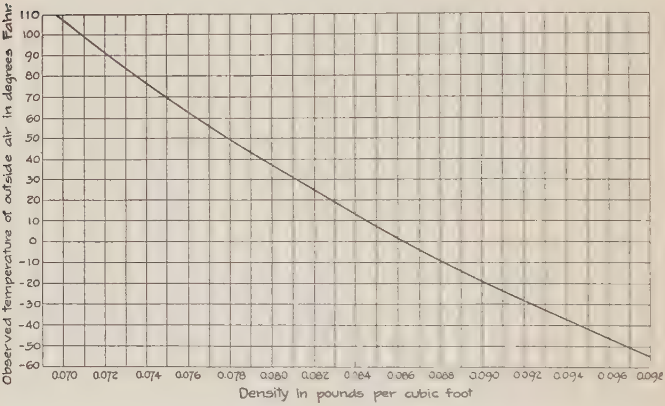

Fig. 6. Density of Outside Air at Various Temperatures. Based on $d_o = 0.08071$ pounds per cu. ft. at 32 deg. Fahr. and $P_o = P = 14.7$ pounds per square inch.

Likewise, the density of the chimney gases is equal to

$$d_c = W_c \frac{P_o}{P} \frac{T}{T_o} \qquad 13$$

in which

TABLE 1

Density and Specific Volume of Air at Various Temperatures

Temperature in degrees Fahr.	Density in pounds per cubic foot	Specific Volume in cubic feet per pound
—50	0.09687	10.32
—40	.09456	10.57
—30	.09236	10.82
—20	.09026	11.08
—10	.08825	11.33
0	.08633	11.58
10	.08449	11.84
20	.08273	12.09
30	.08104	12.34
32	.08071	12.39
40	.07941	12.59
50	.07786	12.84
60	.07636	13.09
70	.07492	13.35
80	.07353	13.60
90	.07219	13.85
100	.07090	14.10
110	.06966	14.35
200	.06015	16.62
250	.05591	17.88
300	.05223	19.14
350	.04901	20.40
400	.04616	21.66
450	.04362	22.92
500	.04135	24.18
550	.03930	25.44
600	.03745	26.70
650	.03576	27.96
700	.03421	29.23
750	.03280	30.49
800	.03150	31.74
850	.03029	33.00
900	.02918	34.26
950	.02815	35.52
1000	.02719	36.78
1100	.02544	39.30
1200	.02391	41.82
1300	.02255	44.34
1400	.02134	46.86
1500	.02025	49.38
1600	.01926	51.90
1700	.01837	54.42
1800	.01756	56.95
1900	.01681	59.46
2000	.01613	61.99

d_c = density of the chimney gases in pounds per cubic foot,
W_c = weight in pounds per cubic foot of chimney gases at 32 degrees Fahr. and standard, or sea level, atmospheric pressure,
T_c = absolute temperature of the chimney gases in degrees Fahr.,
= $t_c + 459.6$, in which t_c is the average temperature of the chimney gases in degrees Fahr.

Fig. 7 shows the variation in the density of the chimney gases for various temperatures, based on two different values for the density at 32 degrees Fahr.

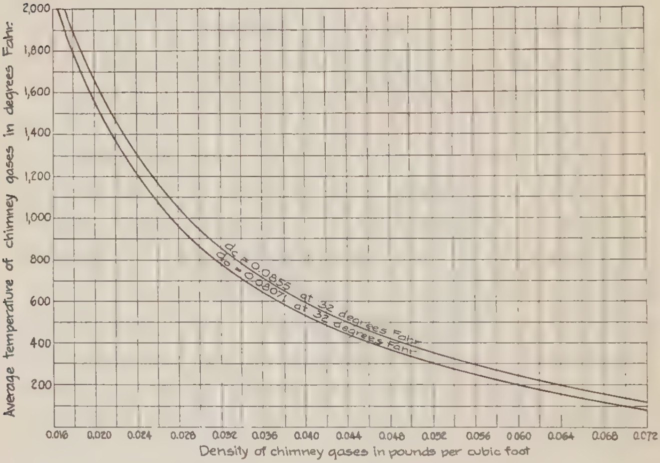

Fig. 7. Density of Chimney Gases at Various Temperatures. Based on $P_o = P = 14.7$ pounds per square inch.

Whence the weight of a column of chimney gases equals

$$H\ d_c = H\ W_c\ \frac{P_o\ T}{P\ T_c} \qquad 14$$

and the weight of an equal column of outside air equals

$$H\ d_o = H\ W_o\ \ P_o\ T \qquad 15$$

both expressed in pounds. Assuming each column to be one square foot in area, the difference in weight between the two columns in pounds per square foot equals

$$H\ d_o - H\ d_c = H\ W_o \frac{P_o\ T}{P\ T_o} - H\ W_c\ \frac{P_o\ T}{P\ T_c}$$

$$= H\ T \frac{P_o}{P}\ \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right) \qquad 16$$

Expressed in inches of water, equation 16 becomes

$$D_t = \frac{H\ T}{5.2}\ \frac{P_o}{P}\ \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right)$$

$$= 0.1923\ H\ T \frac{P_o}{P}\ \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right) \qquad 17$$

in which

H = height of chimney, above grate bars, in feet.
and D_t = theoretical draft in inches of water.
Since $T = 32 + 459.6 = 491.6$,
and $P = 14.7$,

equation 17 reduces to

$$D_t = 6.43\ H\ P_o\ \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right) \qquad 18$$

Equation 18 gives the maximum theoretical static draft with all the observable factors taken into consideration, and is the basis of analysis of all draft problems.

Simplifying further, for convenience, in equation 18:

$$\text{Let } W_o = 0.08071.$$

Assume, for the moment, that the density of the chimney gases is the same as that of the outside air, or,

$$W_c = 0.08071.$$

Substituting these values in equation 18:

$$D_t = 0.519\ H\ P_o \left(\frac{1}{T_o} - \frac{1}{T_c}\right) \qquad 19$$

or

$$= 0.2547H\ B_o \left(\frac{1}{T_o} - \frac{1}{T_c}\right) \qquad 20$$

in which

B_o = observed atmospheric pressure in inches of mercury.

For convenience, let

$$K_D = 0.519P_o \left(\frac{1}{T_o} - \frac{1}{T_c}\right) \qquad 21$$

Then

$$D_t = K_D\ H, \qquad 22$$

Assuming an observed atmospheric pressure, P_o, of 14.7 pounds per square inch, or standard atmospheric pressure, i.e., the atmospheric pressure at sea level, equation 21 becomes

$$K_D = 7.63 \left(\frac{1}{T_o} - \frac{1}{T_c}\right) \qquad 23$$

Table 2 gives the values for K_D, or the theoretical draft per foot of chimney, for various chimney gas and outside air temperatures. Fig. 8 shows the curves for these values. It should be particularly noted that the values shown are based on sea level conditions, i.e., standard atmospheric pressure, and similar outside air and chimney gas densities at 32 degrees Fahr. Table 3 gives the theoretical draft per foot of chimney based on a value of 0.0855 for W_c which may be considered an average value in every day practice.

Fig. 9 gives the theoretical draft for various heights of chimney with the chimney gas temperatures as noted. In constructing this set of curves,

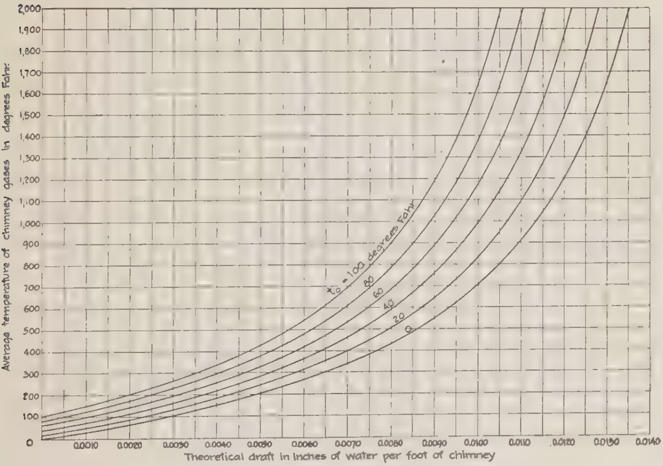

Fig. 8. Theoretical Draft of Chimneys per Foot of Chimney Based on $d_c = d_o = 0.08071$ lbs. per cu. ft. at 32 deg. Fahr. and $P_o = P = 14.7$ lbs. per sq. in.

TABLE 2

THEORETICAL DRAFT OF CHIMNEYS PER FOOT OF CHIMNEY

Based on $d_c = d_0 = 0.08071$ at 32 degrees Fahr., and $P_0 = P = 14.7$

Average temperature of chimney gases in degrees Fahr.	Observed temperature of the outside air in degrees Fahr.												
	0	10	20	30	32	40	50	60	62	70	80	90	100
	Theoretical draft in inches of water per foot of chimney												
0	0												
32	.00108	.00073	.00039	.00006									
60	.00192	.00157	.00123	.00090	.00084	.00059	.00029						
100	.00297	.00262	.00228	.00195	.00189	.00164	.00134	.00105	.00100	.00078	.00051	.00025	
150	.00409	.00374	.00340	.00307	.00301	.00276	.00246	.00217	.00212	.00190	.00163	.00137	.00112
200	.00504	.00469	.00435	.00402	.00396	.00371	.00341	.00312	.00307	.00285	.00258	.00232	.00207
250	.00585	.00549	.00516	.00483	.00477	.00452	.00422	.00393	.00388	.00366	.00339	.00313	.00288
300	.00656	.00621	.00587	.00554	.00548	.00523	.00493	.00464	.00459	.00437	.00410	.00384	.00359
350	.00718	.00683	.00649	.00616	.00610	.00585	.00555	.00526	.00521	.00499	.00472	.00446	.00421
400	.00773	.00738	.00704	.00671	.00665	.00640	.00610	.00581	.00576	.00554	.00527	.00501	.00476
450	.00821	.00786	.00752	.00719	.00713	.00689	.00658	.00629	.00624	.00602	.00575	.00549	.00524
500	.00865	.00830	.00796	.00763	.00757	.00732	.00702	.00673	.00668	.00646	.00619	.00593	.00568
550	.00905	.00870	.00836	.00803	.00797	.00772	.00742	.00713	.00708	.00686	.00659	.00633	.00608
600	.00940	.00905	.00871	.00838	.00832	.00807	.00777	.00748	.00743	.00721	.00694	.00668	.00643
650	.00972	.00937	.00903	.00870	.00864	.00839	.00819	.00780	.00775	.00753	.00726	.00700	.00675
700	.01002	.00967	.00933	.00900	.00894	.00869	.00849	.00810	.00805	.00783	.00756	.00730	.00705
750	.01029	.00994	.00960	.00927	.00921	.00897	.00866	.00837	.00832	.00810	.00783	.00758	.00732
800	.01054	.01019	.00985	.00952	.00946	.00921	.00891	.00862	.00857	.00835	.00808	.00782	.00757
850	.01078	.01043	.01009	.00976	.00970	.00945	.00915	.00886	.00881	.00859	.00832	.00806	.00781
900	.01099	.01064	.01030	.00997	.00991	.00966	.00936	.00907	.00902	.00880	.00853	.00827	.00802
950	.01119	.01084	.01050	.01017	.01011	.00986	.00956	.00927	.00922	.00900	.00873	.00847	.00822
1000	.01138	.01103	.01069	.01036	.01030	.01005	.00975	.00946	.00941	.00919	.00892	.00866	.00841
1100	.01171	.01136	.01102	.01069	.01063	.01038	.01008	.00979	.00974	.00952	.00925	.00899	.00874
1200	.01201	.01166	.01132	.01099	.01093	.01068	.01038	.01009	.01004	.00982	.00955	.00929	.00904
1300	.01227	.01192	.01158	.01125	.01119	.01094	.01064	.01035	.01030	.01008	.00981	.00955	.00930
1400	.01250	.01215	.01181	.01148	.01142	.01117	.01087	.01058	.01053	.01031	.01004	.00978	.00953
1500	.01271	.01236	.01202	.01169	.01163	.01138	.01108	.01079	.01074	.01052	.01025	.00999	.00974
1600	.01290	.01255	.01221	.01188	.01182	.01157	.01127	.01098	.01093	.01071	.01044	.01018	.00993
1700	.01307	.01272	.01238	.01205	.01199	.01174	.01144	.01115	.01110	.01088	.01061	.01035	.01010
1800	.01322	.01287	.01253	.01220	.01214	.01189	.01159	.01130	.01125	.01103	.01076	.01050	.01025
1900	.01337	.01302	.01268	.01235	.01229	.01204	.01174	.01145	.01140	.01118	.01091	.01066	.01040
2000	.01350	.01315	.01281	.01248	.01242	.01217	.01187	.01158	.01153	.01131	.01104	.01078	.01053

TABLE 3

THEORETICAL DRAFT OF CHIMNEYS PER FOOT OF CHIMNEY

Based on $d_o=0.0807$, $d_c=0.0855$, and $P_o=P=14.7$

Average temperature chimney gases in degrees Fahr.	Observed outside air temperature in degrees Fahrenheit										
	0	10	20	30	40	50	60	70	80	90	100
	Draft in inches of water per foot of chimney										
0	0										
32	.00016										
60	.00107	.00072	.00038	.00005							
100	.00216	.00181	.00147	.00114	.00083	.00053	.00024				
150	.00335	.00300	.00266	.00233	.00202	.00172	.00143	.00115	.00089	.00063	.00038
200	.00435	.00400	.00366	.00333	.00302	.00272	.00243	.00215	.00189	.00163	.00138
250	.00521	.00486	.00452	.00419	.00388	.00358	.00329	.00301	.00275	.00249	.00224
300	.00596	.00561	.00527	.00494	.00463	.00433	.00404	.00376	.00350	.00324	.00299
350	.00662	.00627	.00593	.00560	.00529	.00499	.00470	.00442	.00416	.00390	.00365
400	.00720	.00685	.00651	.00618	.00587	.00557	.00528	.00500	.00474	.00448	.00423
450	.00772	.00737	.00703	.00670	.00639	.00609	.00580	.00552	.00526	.00500	.00475
500	.00818	.00783	.00749	.00716	.00685	.00655	.00626	.00598	.00572	.00546	.00521
550	.00860	.00825	.00791	.00758	.00727	.00697	.00668	.00640	.00614	.00588	.00563
600	.00898	.00863	.00829	.00796	.00765	.00735	.00706	.00786	.00652	.00626	.00601
650	.00932	.00897	.00863	.00830	.00799	.00769	.00740	.00712	.00686	.00660	.00635
700	.00963	.00928	.00894	.00861	.00830	.00800	.00771	.00743	.00717	.00691	.00666
750	.00992	.00957	.00923	.00890	.00859	.00829	.00800	.00772	.00746	.00720	.00695
800	.01019	.00984	.00950	.00917	.00886	.00856	.00827	.00799	.00773	.00747	.00722
850	.01043	.01008	.00974	.00941	.00910	.00880	.00851	.00823	.00797	.00771	.00746
900	.01066	.01031	.00997	.00964	.00933	.00903	.00874	.00846	.00820	.00794	.00769
950	.01087	.01052	.01018	.00985	.00954	.00924	.00895	.00867	.00841	.00815	.00790
1000	.01106	.01071	.01037	.01004	.00973	.00943	.00914	.00886	.00860	.00834	.00809
1100	.01142	.01107	.01073	.01040	.01009	.00979	.00950	.00922	.00896	.00870	.00845
1200	.01173	.01138	.01104	.01071	.01040	.01010	.00981	.00953	.00927	.00901	.00876
1300	.01201	.01166	.01132	.01099	.01068	.01038	.01009	.00981	.00955	.00929	.00904
1400	.01226	.01191	.01157	.01124	.01093	.01063	.01934	.01006	.00980	.00954	.00929
1500	.01248	.01213	.01179	.01146	.01115	.01085	.01056	.01028	.01002	.00976	.00951
1600	.01268	.01233	.01199	.01166	.01135	.01105	.01076	.01048	.01022	.00996	.00971
1700	.01286	.01251	.01217	.01184	.01153	.01123	.01094	.01066	.01040	.01014	.00989
1800	.01302	.01267	.01233	.01200	.01169	.01139	.01110	.01082	.01056	.01030	.01005
1900	.01318	.01282	.01249	.01216	.01185	.01155	.01126	.01098	.01072	.01046	.01021
2000	.01332	.01297	.01263	.01230	.01199	.01169	.01140	.01112	.01086	.01060	.01035

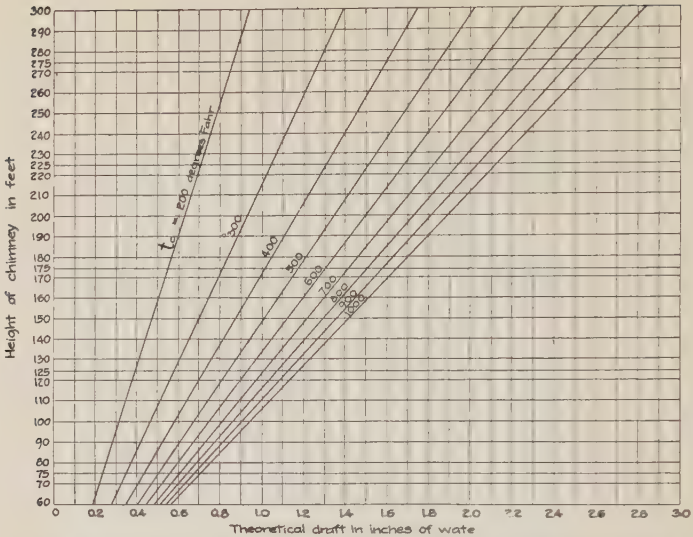

Fig. 9. Theoretical Draft of Chimneys for Various Chimney Gas Temperatures.
Based on $t_o = 60$ deg. Fahr.,
$d_c = d_o = 0.08071$ lbs. per cu. ft. at 32 deg. Fahr., and
$P_o = P = 14.7$ lbs. per sq. in.

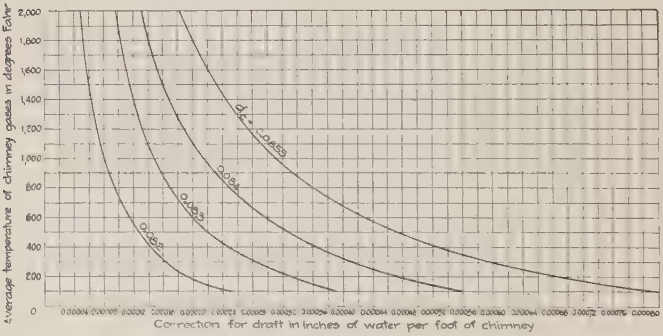

Fig. 10. Correction for Theoretical Draft Due to Chimney Gas Density Variation.

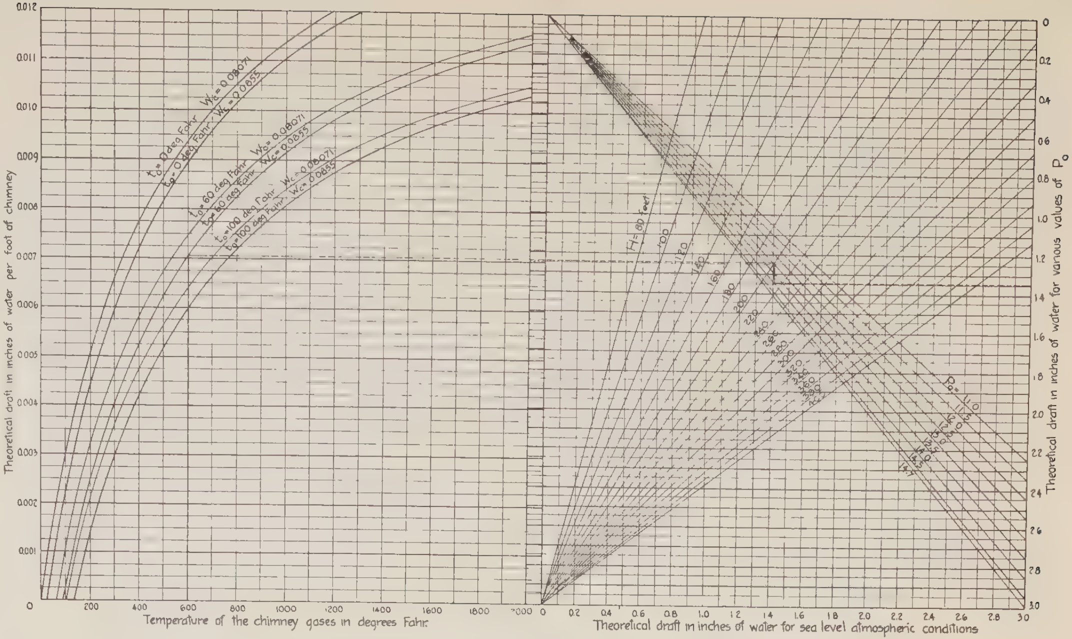

Fig. 11. Chart for determining the theoretical draft of a chimney.

Based on equation $D_t = 6.43\,H\,P_o \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right)$

it has been assumed that the chimney is at sea level, that the density of the chimney gases is the same as that of the outside air, and that the temperature of the outside air is 60 degrees Fahr.

The theoretical draft, as stated before, is purely a theoretical quantity and cannot be accurately observed by a draft gauge. If, however, the ashpit doors be closed tightly, there be no leakage of air through the installation and the gases in the chimney be absolutely motionless, the observed draft at the grate level of the chimney will be approximately the same as the theoretical draft.

The theoretical draft is an extremely important quantity, in that it gives the maximum obtainable intensity of difference in pressure under the conditions as assumed.

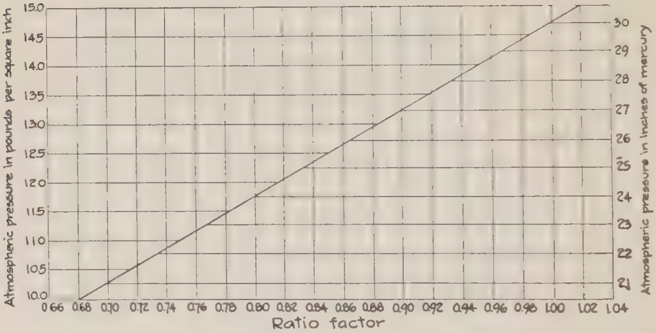

Fig. 12. Variation in Theoretical Draft Due to Atmospheric Pressure Changes.

Summary

The theoretical draft of a chimney increases as

1. The chimney gas temperature increases,
2. The outside air temperature decreases,
3. The chimney gas density decreases,
4. The height of the chimney increases,
5. The atmospheric pressure increases.

Whence the theoretical draft of a chimney varies:

Directly as 1. The chimney gas temperature,
2. The height of the chimney,
3. The atmospheric pressure,
and inversely as 1. The outside air temperature,
2. The density of the chimney gases.

Example

Find the theoretical draft of a chimney under the following conditions:

80 degrees Fahr., outside air temperature,
500 degrees Fahr., chimney gas temperature,
0.0855 density of the chimney gases,
200 feet, height of chimney,
14.5 pounds per square inch, atmospheric pressure.

Substituting the above values in equation 18 and reducing:

$$D_t = 6.43 \times 200 \times 14.5 \times \left(\frac{0.08071}{539.6} - \frac{0.0855}{959.6} \right)$$

$$= 1.128 \text{ inches of water.}$$

From Table 2 or Fig. 8:

$K_D = 0.00619.$

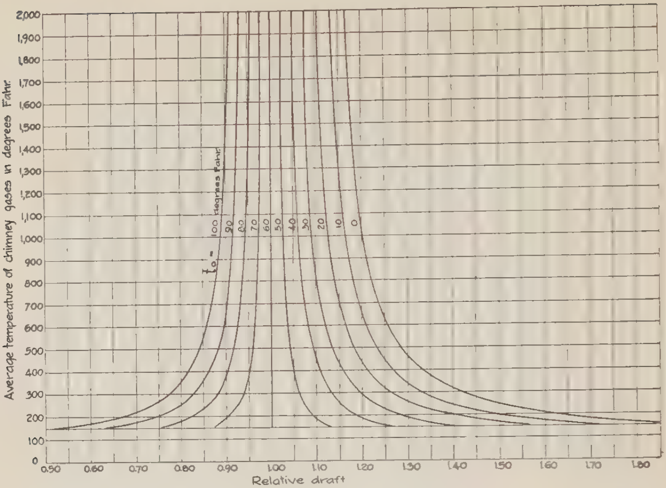

Fig. 13. Relation of Theoretical Draft for Various Outside Air Temperatures to the Draft for an Outside Air Temperature of 60 deg. Fahr.

Based on $d_c = d_o = 0.08071$ at 32 deg. Fahr.
and $P_o = P = 14.7$ lbs. per sq. in.

From Fig. 10, the correction for a chimney gas density of 0.0855 equals

0.00047.

Whence the corrected theoretical draft per foot of chimney equals

$0.00619 - 0.00047 = 0.00572$, (See Table 3)

and for a 200-foot chimney

$0.00572 \times 200 = 1.144.$

The ratio factor for an atmospheric pressure of 14.5 pounds per square inch, as given by Fig. 12, equals 0.986

Whence the final corrected theoretical draft equals

$1.144 \times 0.986 = 1.128$ inches of water.

Again, from Fig. 9:

$D_t = 1.34$ inches of water.

From Fig. 10, the correction for a chimney gas density of 0.0855 equals

$0.00047 \times 200 = 0.09.$

Whence the theoretical draft corrected for density equals

$1.34 - 0.09 = 1.25$ inches of water.

From Fig. 13, the relative draft for an outside air temperature of 80 degrees Fahr. and a chimney gas temperature of 500 degrees equals

0.92,

and from Fig. 12, the ratio factor for an atmospheric pressure of 14.5 pounds per square inch equals

0.986

Whence the final corrected theoretical draft equals

$1.25 \times 0.92 \times 0.986 = 1.13$ inches of water.

CHAPTER III

LOSSES DUE TO VELOCITY AND FRICTION

As has been stated, heretofore the theoretical draft as given by equation 18 is purely a theoretical quantity which cannot be accurately measured or indicated by a draft gauge. If, however, the ash-pit doors or air entrance be closed tightly, there be no leakage of air in the installation, and there be no movement or circulation of gases within the chimney, the observed draft at any region of the chimney will be approximately the same as the theoretical draft. When the gases within the chimney are flowing freely, the intensity of the theoretical draft is decreased by:

1. Loss of draft due to velocity of the chimney gases,

2. Loss of draft due to friction between the chimney gases and the walls of the chimney.

The quantity obtained by deducting the values of the losses due to velocity and friction from the theoretical draft is called the available draft. The intensity of the available draft may be observed when the gases within the chimney are flowing freely and there are no obstructions in the chimney preventing an easy egress of the gases. The available draft is useful as the balancing member of an equation when the draft at the damper level is considered. The draft observed at the chimney side of the damper is the *available* draft and that required at the boiler side is called the *required* draft.

Whence $$D_a = D_t - (h_v + h_f) \qquad 24$$

in which

D_a = available draft in inches of water,
h_v = loss of draft due to velocity in inches of water,
h_f = loss of draft due to friction in inches of water.

Loss of Draft Due to Velocity Based on Velocity of Chimney Gases

The equation for the loss of draft due to the velocity of the chimney gases within the chimney, or, the amount of draft necessary to impart velocity to the gases going up the chimney, commonly called the velocity head, is derived as follows:

Now $$V_a = \sqrt{2\,g\,h}$$

whence $$h = \frac{V^2_a}{2g} \qquad 25$$

Expressed in terms of gases and inches of water, equation 27 becomes

$$h_v = 0.192\, d_c \frac{V^2_a}{2g} \qquad 26$$

or $$h_v = 0.192\, W_c \frac{P_o}{P}\,\frac{T}{T_c}\,\frac{V^2}{2g} \qquad 27$$

in which

V_a = working velocity of chimney gases in ft. per second,
g = acceleration due to gravity.

Now since $P = 14.7$
$T = 491.6$

and $2g = 64.4$

Then $h_v = 0.10\, W_c\, P_o \dfrac{V^2_a}{T_c}$ 28

Equation 28 gives the loss of draft due to velocity of the chimney gases with all of the observable factors taken into consideration.

Assuming $W_c = W_o = 0.08071$

Then $h_v = 0.00806\, P_o \dfrac{V^2_a}{T_c}$ 29

Again, assuming $P_o = P = 14.7$

Then $h_v = 0.1185 \dfrac{V^2_a}{T_c}$ 30

Equation 30 gives the loss of draft due to velocity in its simplest form. Table 4 gives the loss of draft due to velocity for various chimney temperatures with the velocities as shown, based on a chimney gas density of 0.08071 pounds per cubic foot at 32 degrees Fahr. and $P_o = P = 14.7$. Fig. 14 shows these results graphically.

The loss of draft due to velocity may also be considered as the amount of draft, or difference in pressure, required to accelerate the chimney gases. It should, in reality, be considered as a part of the loss of draft due to friction, but since the loss of draft due to friction is dependent upon the height of the chimney and also upon the value of D, neither one of which affects the intensity of the loss of draft due to velocity, it is necessary to consider each separately.

The correction factor, or ratio factor, for atmospheric pressure changes is given by Fig. 12 and for chimney gas density changes by Fig. 15.

TABLE 4

LOSS OF DRAFT DUE TO VELOCITY

Based on density of chimney gases = 0.08071 pounds per cubic foot at 32 degrees Fahr., and $P_o = P = 14.7$ pounds per square inch.

Average temperature of chimney gases in deg. Fahr.	Velocity of chimney gases in feet per second									
	5	10	15	20	25	30	35	40	45	50
	Loss of draft due to velocity in inches of water									
100	.005	.021	.048	.085	.132	.190	.259	.338	.428	.528
200	.005	.018	.040	.072	.112	.161	.220	.287	.364	.448
300	.004	.016	.035	.062	.097	.140	.191	.249	.316	.390
400	.003	.014	.031	.055	.086	.124	.169	.220	.279	.344
500	.003	.012	.028	.049	.077	.111	.151	.197	.250	.308
600	.003	.011	.025	.045	.070	.100	.137	.179	.226	.279
700	.003	.010	.023	.041	.064	.092	.125	.163	.207	.255
800	.002	.009	.021	.038	.059	.085	.115	.150	.190	.235
900	.002	.009	.020	.035	.054	.078	.107	.139	.176	.218
1000	.002	.008	.018	.032	.051	.073	.099	.130	.164	.202
1100	.002	.008	.017	.030	.047	.068	.093	.121	.154	.190
1200	.002	.007	.016	.029	.044	.064	.088	.114	.145	.178
1300	.002	.007	.015	.027	.042	.061	.083	.108	.136	.168
1400	.002	.006	.014	.025	.040	.057	.078	.102	.128	.159
1500	.002	.006	.014	.024	.038	.054	.074	.097	.122	.151
1600	.001	.006	.013	.023	.036	.052	.070	.092	.116	.144
1700	.001	.005	.012	.022	.034	.049	.067	.088	.111	.137
1800	.001	.005	.012	.021	.033	.047	.064	.084	.106	.131
1900	.001	.005	.011	.020	.031	.045	.061	.080	.102	.125
2000	.001	.005	.011	.019	.030	.043	.059	.077	.098	.120

Example: Determine the loss of draft due to velocity for the following conditions:

600 degrees Fahr. chimney gas temperature,

30 feet per second velocity of the chimney gases,

0.0855 density of the chimney gases at 32 degrees Fahr.,

14.3 pounds per square inch atmospheric pressure.

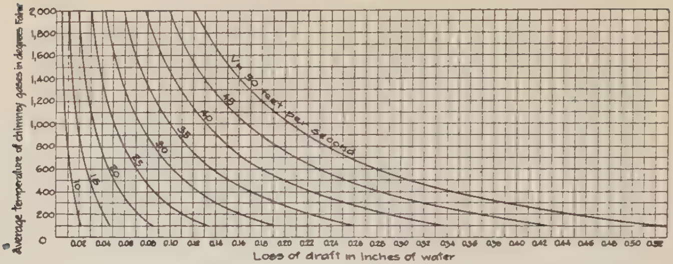

Fig. 14. Loss of Draft Due to Velocity.
Based on $d_c = 0.08071$ pounds per cubic foot at 32 degrees Fahr.
and
$P_o = P = 14.7$ pounds per square inch.

Substituting in equation 28 and reducing:

$$h_v = 0.10 \times 0.0855 \times 14.3 \times \frac{(30)^2}{1059.6}$$

$$= 0.103 \text{ inches of water}$$

Or, from Fig. 14 or Table 4, the loss of draft due to velocity for a chimney gas density of 0.08071 lbs. per cu. ft. at 32 deg. Fahr. and standard atmospheric pressure equals

0.100 inches of water.

From Fig. 12, the ratio factor for an atmospheric pressure of 14.3 lbs. per square inch equals 0.973, and from Fig. 15, the ratio factor for a chimney gas density of 0.0855 equals 1.059.

Whence the loss of draft due to velocity corrected for chimney gas density and atmospheric pressure equals

$$0.100 \times 0.973 \times 1.059$$

$$= 0.103 \text{ inches of water.}$$

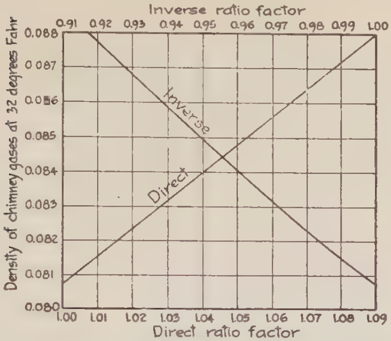

Fig. 15. Ratio Factor for Losses of Draft Due to Velocity and Friction Due to Chimney Gas Density Variations.

Loss of Draft Due to Velocity Based on Volume of Chimney Gases

Considering the volume of the chimney gases, instead of the velocity, the loss of draft due to velocity is derived as follows:

Since $Q = AV_a$ 31

Then $V_a = \frac{Q}{A}$ 32

in which Q = volume of gases flowing in cubic feet per second, and A = area of chimney in square feet.

Substituting in equation 28:

$$h_v = 0.10\ W_c P_o \frac{Q^2}{A^2 T_c} \qquad 33$$

For circular sections:

$$h_v = 0.162\ W_c P_o \frac{Q^2}{D^4 T_c} \qquad 34$$

Assuming $W_c = W_o = 0.08071$:

$$h_v = 0.013\ P_o \frac{Q^2}{D^4\, T_c} \tag{35}$$

Assuming $P_o = P\ 14.7$:

$$h_v = 0.193\ \frac{Q^2}{D^4\, T_c} \tag{36}$$

Finally, assuming $T_c = 1059.6\ (600 + 459.6)$:

$$h_v = 0.000182 \frac{Q^2}{D^4} \tag{37}$$

Fig. 16 gives the loss of draft due to velocity for various values of Q and D, based on a chimney gas density of 0.08071 pounds per cubic foot at 32 de-

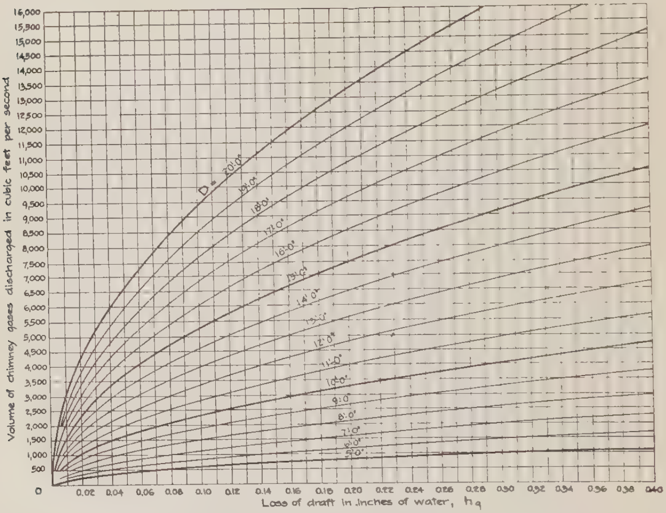

Fig. 16. Loss of Draft Due to Velocity Based on Volume of Chimney Gases Flowing.
Based on a circular section, $W_c = 0.08071$, $t_c = 600$ deg. Fahr., and $P_o = P = 14.7$ lbs. per sq.in.

grees Fahr., $P_0 = P = 14.7$, and a chimney gas temperature of 600 degrees Fahr. The correction or ratio factor for a variation in the atmospheric pressure is given by Fig. 12, for a variation in the density of the chimney gases by Fig. 15 and for a variation in the temperature of the chimney gases by Fig. 17. Table 5 gives the fourth power of various values of D.

Loss of Draft Due to Velocity Based on the Weight of the Chimney Gases

Considering the weight of the chimney gases, instead of the velocity or the volume, the loss of draft due to velocity is derived as follows:

TABLE 5.
FOURTH POWERS OF D

D	D^4	D	D^4
1.0	1	11.0	14,641
1.5	5	11.5	17,490
2.0	16	12.0	20,736
2.5	39	12.5	24,414
3.0	81	13.0	28,561
3.5	150	13.5	33,215
4.0	256	14.0	38,416
4.5	410	14.5	44,205
5.0	625	15.0	50,625
5.5	915	15.5	57,720
6.0	1,296	16.0	65,536
6.5	1,785	16.5	74,120
7.0	2,401	17.0	83,521
7.5	3,164	17.5	93,789
8.0	4,096	18.0	104,976
8.5	5,220	18.5	117,135
9.0	6,561	19.0	130,321
9.5	8,145	19.5	144,590
10.0	10,000	20.0	160,000
10.5	12,155		

Now from equation 8:

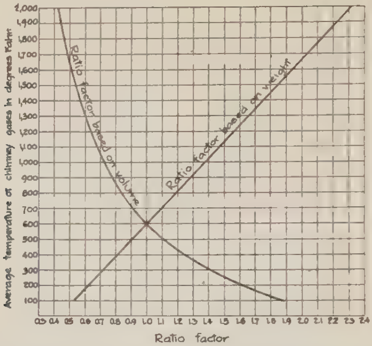

Fig. 17. Ratio Factor for Losses of Draft Due to Velocity and Friction Due to Chimney Gas Temperature Changes.

$$Q = \frac{W_a R\ T_c}{P_o} \qquad 38$$

Also $Q = AV_a$

Then $$AV_a = \frac{W_a R\ T_c}{P_o} \qquad 39$$

and $$V_a = \frac{W_a R\ T_c}{A\ P_o} \qquad 40$$

Substituting equation 11 in equation 40:

$$V_a = \frac{W_a\ P\ T_c}{A\ T\ P_o\ W_c}$$

$$= 0.03\ \frac{W_a\ T_c}{P_o\ A\ W_c}. \qquad 41$$

Substituting equation 41 in equation 28:

$$h_v = 0.10\ W_c\ P_o\ \frac{\left(0.03\ \frac{W_a\ T_c}{P_o\ A\ W_c}\right)^2}{T_c}$$

$$= 0.0000893 \frac{W^2_a T_c}{P_o A^2 W_c} \qquad 42$$

Now since $P = 0.4912 \ B_o$

Then $$h_v = 0.000182 \frac{W^2_a T_c}{B_o A^2 W_c} \qquad 43$$

For a circular section:

$$h_v = 0.000145 \frac{W^2_a T_c}{P_o D^4 W_c} \qquad 44$$

For $P_o = P = 14.7$:

$$h_v = 0.00000986 \frac{W^2_a T_c}{D^4 W_c} \qquad 45$$

For $W_c = W_o = 0.08071$:

$$h_v = 0.0001222 \frac{W^2_a T_c}{D^4} \qquad 46$$

For $T_c = 1059.6 \ (600 + 459.6)$:

$$h_v = 0.01295 \frac{W^2_a}{D^4} \qquad 47$$

Fig. 18 gives the loss of draft due to velocity for various values of W and D, based on a chimney gas density of 0.08071 pounds per cubic foot at 32 degrees Fahr., $P_o = P = 14.7$, and a chimney gas temperature of 600 degrees Fahr. The correction or ratio factor for a variation in the atmospheric pressure is given by Fig. 19, for a variation in the density of the chimney gases by Fig. 15, and for a variation in the temperature of the chimney gases by Fig. 17. Table 5 gives the fourth power of various values of D.

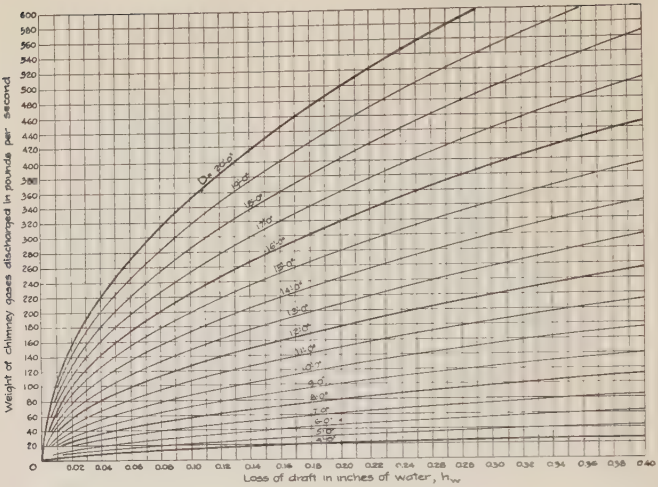

Fig. 18. Loss of Draft Due to Velocity Based on Weight of Chimney Gases Flowing.

Based on a circular section, $W_c = 0.08071$, $t_c = 600$ deg. Fahr. and $P_0 = P = 14.7$ lbs. per sq. in.

The shape of the cross-section of the chimney has no effect on the intensity of the loss of draft due to velocity when the loss is based on the velocity of the chimney gases. When the loss is based on the volume or weight of the chimney gases flowing, however, the intensity of the loss for a square section is 0.617 of that for a circular section, where D = length of side of square; and for an octagonal section, 0.90 of that for a circular section, where D = length of face to face dimension of inside octagon.

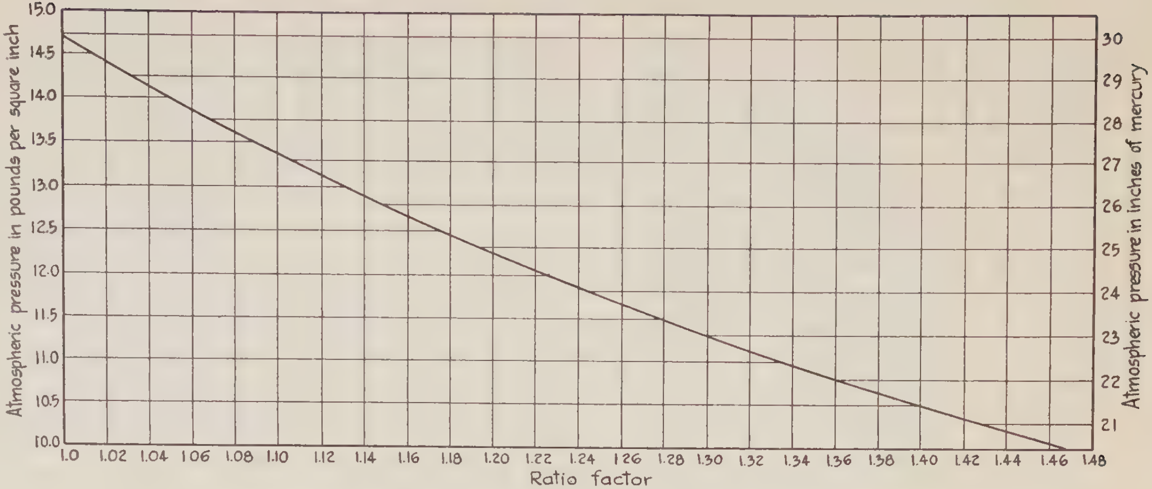

Fig. 19. Variation in losses due to velocity and friction due to atmospheric pressure changes.

Loss of Draft Due to Friction Based on the Velocity of the Chimney Gases

The loss of draft due to friction between the chimney gases and the interior walls of the chimney may be derived from Fanning's equation as follows:

Fanning's equation is $$h = f \frac{V^2_a L}{2gC_d} \qquad 48$$

Expressed in terms of gases and inches of water:

$$h_f = 0.192\ f\ d_c \frac{V^2_a\ L}{2g\ C_d} \qquad 49$$

in which f = coefficient of friction,
L = height of chimney, or length of duct, in feet,
C_d = hydraulic radius of section.

Whence $$h_f = 0.192\ f\ W_c \frac{P_o\ T\ V^2_a\ L}{P\ T_c\ 2g\ C_d} \qquad 50$$

Now since $P = 14.7$
$T = 491.6$
and $2g = 64.4$

Then $$h_f = 0.10\ f\ W_c\ P_o \frac{V^2_a}{T_c} \frac{L}{C_d} \qquad 51$$

Equation 51 gives the loss of draft due to friction with all of the observable factors taken into consideration. This equation may be considerably simplified as follows:

For a circular section:

$$C_d = \frac{A}{C} = \frac{D}{4} \qquad 52$$

in which A = area of section in square feet,
C = perimeter of section in feet,
D = diameter of section in feet.

Whence $$h_f = 0.40\ f\ W_c\ P_o \frac{V^2_a}{T_c} \frac{L}{D} \qquad 53$$

Assuming $P_o = P = 14.7$:

$$h_f = 5.88\, f\, W_c \frac{V^2_a}{T_c} \frac{L}{D} \qquad 54$$

Assuming $W_c = W_o = 0.08071$:

$$h_f = 0.4746\, f \frac{V^2_a}{T_c} \frac{L}{D} \qquad 55$$

The value of f, the coefficient of friction, is determined by experiment and varies between wide limits according to various authorities. Further experimentation to determine the value of this coefficient of friction more accurately is badly needed. An average of several experiments together with values recommended by several authorities gives the following values:

f = 0.016 for brick and brick-lined ducts,
= 0.012 for unlined steel ducts.

Due to the fact that the inside surface of both masonry and metal ducts, or chimneys, becomes in time covered with soot, the coefficient of friction no doubt is practically the same for both and in all probability approaches the higher value noted above.

Whence $$h_f = 0.0076 \frac{V^2_a L}{T_c D} \qquad 56$$

Assuming, for convenience, that D = 1 foot, and L = 1 foot,

then $$h_f = 0.0076 \frac{V^2_a}{T_c} \qquad 57$$

Table 6 gives the loss of draft due to friction per foot of chimney for various chimney gas temperatures with the chimney gas velocities as noted, and based on $P_o = P = 14.7$ lbs. per square inch,

TABLE 6

LOSS OF DRAFT DUE TO FRICTION

Based on L = 1 foot, D = 1 foot, density of chimney gases = 0.08071 pounds per cubic foot at 32 degrees Fahr., f = 0.016, and $P_0 = P = 14.7$ pounds per square inch

Average temperature of chimney gases in degrees Fahr.	Velocity of chimney gases in feet per second									
	5	10	15	20	25	30	35	40	45	50
	Loss of draft due to friction in inches of water per foot of duct									
100	.00034	.00135	.00304	.00541	.00845	.01216	.01656	.02163	.02737	.03380
200	.00029	.00115	.00258	.00460	.00717	.01032	.01405	.01835	.02323	.02867
300	.00025	.00100	.00224	.00399	.00623	.00896	.01220	.01594	.02017	.02490
400	.00022	.00088	.00198	.00352	.00550	.00792	.01078	.01409	.01785	.02201
500	.00020	.00079	.00177	.00316	.00493	.00710	.00966	.01262	.01597	.01971
600	.00018	.00072	.00161	.00286	.00446	.00643	.00875	.01142	.01446	.01785
700	.00016	.00065	.00147	.00261	.00408	.00587	.00800	.01044	.01321	.01631
800	.00015	.00060	.00135	.00240	.00376	.00541	.00736	.00961	.01217	.01502
900	.00014	.00056	.00125	.00223	.00348	.00501	.00682	.00891	.01127	.01391
1000	.00013	.00052	.00117	.00208	.00324	.00466	.00635	.00830	.01050	.01297
1100	.00012	.00049	.00109	.00194	.00304	.00437	.00594	.00777	.00983	.01213
1200	.00011	.00046	.00103	.00182	.00285	.00410	.00559	.00730	.00923	.01140
1300	.00011	.00043	.00097	.00172	.00269	.00387	.00527	.00688	.00871	.01075
1400	.00010	.00041	.00092	.00163	.00254	.00366	.00499	.00651	.00824	.01017
1500	.00010	.00039	.00087	.00155	.00241	.00348	.00473	.00618	.00782	.00966
1600	.00009	.00037	.00083	.00147	.00230	.00331	.00450	.00588	.00744	.00919
1700	.00009	.00035	.00079	.00140	.00220	.00315	.00429	.00561	.00709	.00876
1800	.00008	.00034	.00075	.00134	.00310	.00301	.00410	.00536	.00678	.00837
1900	.00008	.00032	.00072	.00128	.00200	.00288	.00393	.00513	.00649	.00802
2000	.00008	.00031	.00069	.00123	.00193	.00277	.00377	.00492	.00623	.00769

$d_c = 0.08071$ pounds per cubic foot at 32 degrees Fahr., $f = 0.016$, and $D = 1$ foot. Fig. 20 shows these results graphically.

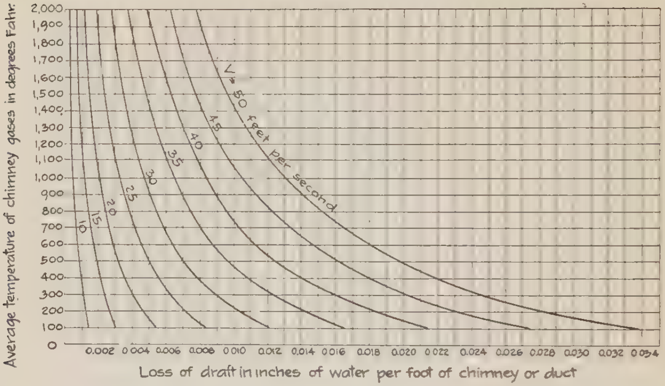

Fig. 20. Loss of Draft Due to Friction per Foot of Chimney or Duct.
Based on $d_c = 0.0871$ pounds per cubic foot at 32 degrees Fahr., $P_0 = P = 14.7$ pounds per square inch, $f = 0.016$, and $D = 1$ ft.

The correction or ratio factor for a variation in the atmospheric pressure is given by Fig. 12, for a variation in the density of the chimney gases by Fig. 15, for a variation in the temperature of the chimney gases by Fig. 17, for a variation in the diameter of the chimney by Fig. 21, and for a variation in the coefficient of friction by Fig. 22.

The results as given by Table 6 and Fig. 20 are per foot of duct, or height of chimney. For any height of chimney, then, the loss of draft due to friction is equal to the loss per foot multiplied by the height of the chimney under consideration.

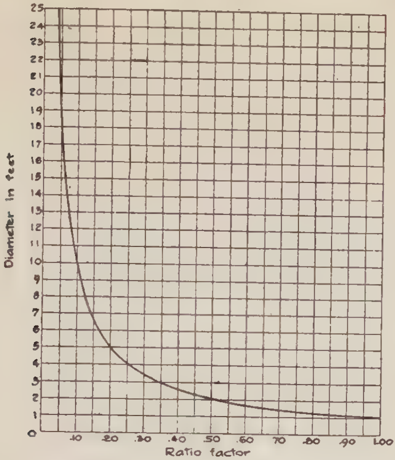

Fig. 21. Ratio Factor for Variation in the Value of D.

Example: Determine the loss of draft due to friction for the following conditions:

600 degrees Fahr. chimney gas temperature,
30 feet per second chimney gas velocity,
0.0855 density of the chimney gases,
0.016 coefficient of friction,
14.3 pounds per square inch atmospheric pressure, circular section,
150 feet height of chimney or length of duct,
5 feet diameter of duct.

Substituting in equation 51 and reducing:

$$h_f = 0.10 \times 0.016 \times 0.0855 \times 14.3 \times \frac{(30)^2}{1059.6} \times \frac{150}{\dfrac{\frac{\pi}{4}(5)^2}{\pi\ 5}}$$

$= 0.198$ inches of water

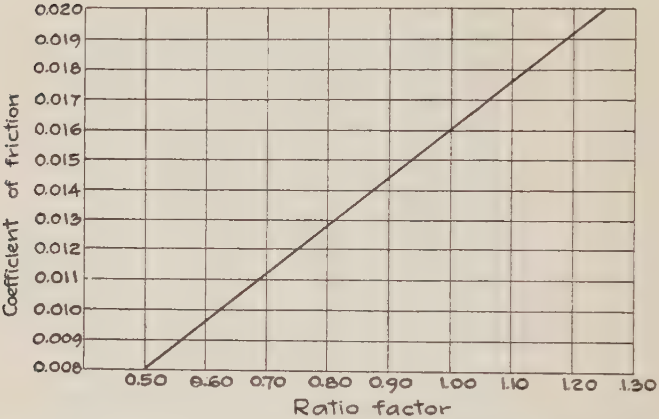

Fig. 22. Ratio Factor for Variation in Coefficient of Friction.

Or, from Fig. 20 or Table 6, the loss of draft due to friction per foot of duct per foot of diameter for a chimney gas density of 0.08071 pounds per cubic foot at 32 degrees Fahr. and standard atmospheric pressure equals 0.0064 inches of water.

From Fig. 12, the ratio factor for an atmospheric pressure of 14.3 pounds per square inch equals 0.973.

From Fig. 15, the ratio factor for a chimney gas density of 0.0855 pounds per cubic foot at 32 degrees Fahr. equals 1.059.

From Fig. 21, the ratio factor for a diameter of 5 feet equals 0.20.

Whence the corrected loss of draft per foot of duct equals

$$0.0064 \times 0.973 \times 1.059 \times 0.20$$
$$= 0.00132 \text{ inches of water,}$$

and for a duct 150 feet long the loss of draft due to friction equals

$$0.00132 \times 150$$
$$= 0.198 \text{ inches of water.}$$

If the coefficient of friction is 0.012, the ratio factor from Fig. 22 equals 0.75, and the loss of draft due to friction equals

$$0.198 \times 0.75$$
$$= 0.149 \text{ inches of water.}$$

In determining the loss of draft due to friction, care should be taken in selecting the proper value for L. If the bottom of the breeching is located at the bottom of the shaft or at the top of the foundation, or more correctly at or near the grate level of the boilers, then $L = H$ and the length of the duct is equal to the height of the chimney. In most installations, however, the bottom of the breeching opening is considerably above the grate level and in many cases is between 15 and 20 feet above this datum plane. In this case, the length of the duct, L, is equal to the distance from the bottom of the breeching opening to the top of the chimney, or the distance over which the chimney gases travel. In the example under discussion, if the bottom of the breeching opening is located 20 ft. 0 in. above the grate level, then the loss of draft due to friction will be equal to

$$0.00132 \times 130$$
$$= 0.172 \text{ inches of water.}$$

Loss of Draft Due to Friction Based on Volume of Chimney Gases.

Considering the volume of the chimney gases instead of the velocity, the loss of draft due to friction is derived as follows:

Substituting equation 32 in equation 51:

$$h_f = 0.10\, f\, W_c\, P_o\, \frac{Q^2}{A^2\, T_c}\, \frac{L}{C_r} \qquad 58$$

For a circular section, as before:

$$h_f = 0.647\, f\, W_c\, P_o\, \frac{Q^2}{T_c}\, \frac{L}{D^5} \qquad 59$$

For $P_o = P = 14.7$:

$$h_f = 9.515\, f\, W_c\, \frac{Q^2}{T_c}\, \frac{L}{D^5} \qquad 60$$

For $W_c = W_o = 0.08071$:

$$h_f = 0.768\, f\, \frac{Q^2}{T_c}\, \frac{L}{D^5} \qquad 61$$

For $f = 0.016$:

$$h_f = 0.0123\, \frac{Q^2}{T_c}\, \frac{L}{D^5} \qquad 62$$

Assuming a chimney gas temperature of 600 degrees Fahr., the loss of draft due to friction per foot of duct is equal to:

$$h_f = 0.0000116\, \frac{Q^2}{D^5} \qquad 63$$

Fig. 23 gives the loss of draft due to friction for various values of Q and D, based on a circular section, $P_o = P = 14.7$, $W_c = W_o = 0.08071$, $f = 0.016$, and a chimney gas temperature of 600 degrees Fahr. The curves give the friction loss per foot of duct. The correction or ratio factor for a variation in the atmospheric pressure is given by Fig. 12, for a variation in the density of the chimney gases by Fig. 15, for a variation in the temperature of the chimney gases by Fig. 17, and for a variation in the coefficient of friction by Fig. 22. Fig. 24 is an enlargement of a section of Fig. 23 giving the loss due to friction for several of the smaller diameters.

The loss of draft due to friction for an octagonal section is 0.90 and for a square section 0.617 of that for a circular section, for the same value of Q and D, and in which D = length of side of square for square section and D = face to face dimension of octagon section.

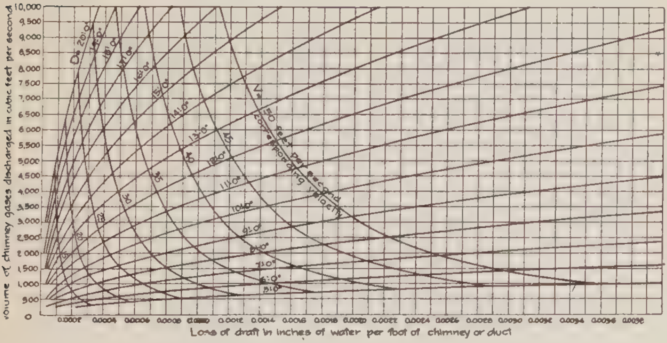

Fig. 23. Loss of Draft Due to Friction for Various Volumes of Chimney Gases and Diameters of Chimney.

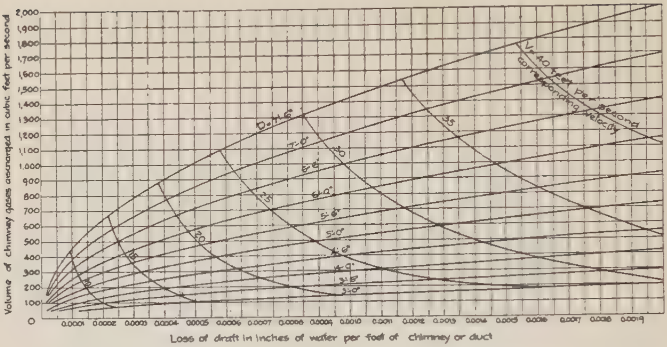

Fig. 24. Enlarged Section of Fig. 22.

Both Figures based on a chimney with a circular section, 600 degrees Fahr. chimney gas temperature, 0.016 coefficient of friction, 0.08071 chimney gas density at 32 degrees Fahr., and $P_0 = P = 14.7$ pounds per square inch.

Since $Q = A V_a$, equation 63 may also be written as

$$h_f = 0.0000116 \frac{A^2 V_a^2}{D^5} \qquad 64$$

Since A is a function of both Q and D, V_a then is the corresponding velocity of the chimney gases in feet per second and the curves for various corresponding velocities are shown on Figs. 23 and 24.

Table 7 gives the fifth power for various values of D.

Loss of Draft Due to Friction Based on the Weight of the Chimney Gases

Considering the weight of the chimney gases instead of the velocity or the volume, the loss of draft due to friction is derived as follows:

Substituting equation 41 in equation 51:

TABLE 7

FIFTH POWERS OF D

D	D^5	D	D^5
1.0	1	11.0	161,051
1.5	8	11.5	201,135
2.0	32	12.0	248,832
2.5	97	12.5	305,175
3.0	243	13.0	371,293
3.5	525	13.5	448,268
4.0	1,024	14.0	537,824
4.5	1,845	14.5	640,973
5.0	3,125	15.0	759,375
5.5	5,033	15.5	894,660
6.0	7,776	16.0	1,048,576
6.5	11,603	16.5	1,222,980
7.0	16,807	17.0	1,419,857
7.5	23,730	17.5	1,641,307
8.0	32,768	18.0	1,889,568
8.5	44,370	18.5	2,166,998
9.0	59,049	19.0	2,476,099
9.5	77,387	19.5	2,819,505
10.0	100,000	20.0	3,200,000
10.5	127,628		

$$h_f = 0.10\, f\, W_c\, P_o \frac{\left(0.03 \frac{W_a\, T_c}{P_o\, A\, W_c}\right)^2}{T_c} \frac{L}{C_d} \qquad 65$$

$$= 0.0000893\, f\, W_c\, P_o \frac{W_a^2\, T_c^2}{T_c\, P_o^2\, A^2\, W_c^2} \frac{L}{C_d}$$

Then $$h_f = 0.0000893\, f \frac{W_a^2\, T_c}{P_o\, A^2\, W_c} \frac{L}{C_d} \qquad 66$$

Or $$h_v = 0.000182\, f\, \frac{W^2_a\, T_c}{B_o\, A^2\, W_c}\, \frac{L}{C_d} \qquad 67$$

In general $C_d = \frac{A}{C}$.

For a circular section

$$h_f = 0.000579\, f\, \frac{W^2_a\, T_c\, L}{P_o\, D^5\, W_c} \qquad 68$$

Assuming $P_o = P = 14.7$:

$$h_f = 0.0000394\, f\, \frac{W^2_a\, T_c\, L}{D^5\ \ W_c} \qquad 69$$

Assuming $W_c = W_o = 0.08071$:

$$h_f = 0.000488\, f\, \frac{W^2_a\, T_c\, L}{D^5} \qquad 70$$

Assuming $f = 0.016$:

$$h_f = 0.0000078\, \frac{W^2_a\, T_c\, L}{D^5} \qquad 71$$

Finally, assuming a chimney gas temperature of 600 degrees Fahr., the loss of draft due to friction per foot of duct is equal to:

$$h_f = 0.00828\, \frac{W^2_a}{D^5} \qquad 72$$

Fig. 25 gives the loss of draft due to friction for various values of W and D, based on a circular section, $P_o = P = 14.7$, $W_c = W_o = 0.08071$, $f = 0.016$, and a chimney gas temperature of 600 degrees Fahr. The curves give the friction loss per foot of duct. The correction or ratio factor for a variation in the atmospheric pressure is given by Fig. 19, for a variation in the density of the chimney gases by Fig. 15, for a variation in the temperature of the chimney gases by Fig. 17, and for a variation in the coefficient of friction by Fig. 22. Fig. 26 is an enlargement of a section of Fig. 25

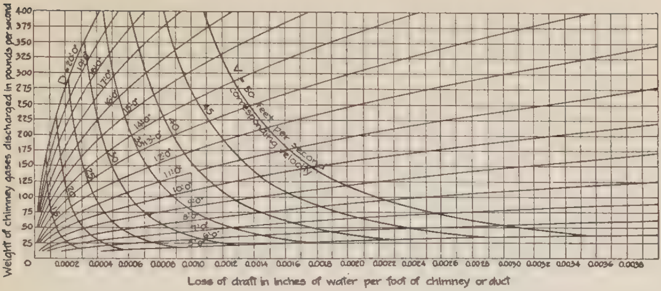

Fig. 25. Loss of Draft Due to Friction for Various Weights of Chimney Gases and Diameters of Chimney.

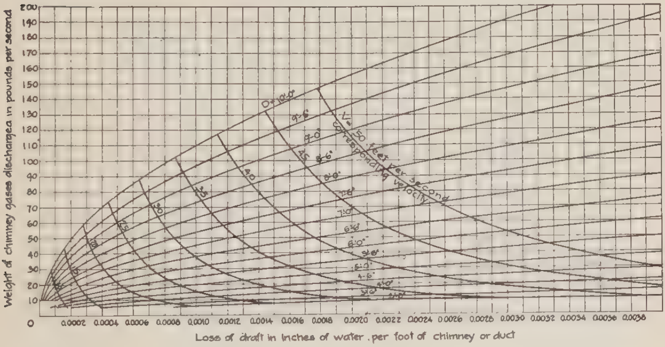

Fig. 26. Enlarged Section of Fig. 24.

Both Figures based on a chimney with a circular section, 600 degrees Fahr. chimney gas temperature, 0.016 coefficient of friction, 0.08071 density of chimney gases at 32 deg. Fahr., and $P_o = P = 14.7$ lbs. per sq. in.

giving the loss due to friction for several of the smaller velocities.

As stated heretofore, the loss of draft due to friction for an octagonal section is 0.90 and for a square section 0.617 of that for a circular section, for the same value of W and D.

Since $Q = AV_a$

and also $$Q = \frac{W_a R T_c}{P_o} \qquad 73$$

Then $$W_a = \frac{Q\ P_o}{R\ T_c} \qquad 74$$

$$= \frac{A V_a P_o}{R T_c} \qquad 75$$

For a chimney gas density of 0.08071 pounds per cubic foot at 32 degrees Fahr., $P_o = P = 14.7$, and a chimney gas temperature of 600 degrees Fahr.,

$$W^2_a = \frac{A^2 V^2_a}{713} \qquad 76$$

Substituting in equation 72:

$$h_f = 0.00828\ \frac{A^2 V^2_a}{713\ D^5} \qquad 77$$

Then, as before, since A bears a known relation to D, V is the corresponding velocity of the chimney gases in feet per second. The curves for the various velocities are shown on Figs. 25 and 26.

CHAPTER IV

AVAILABLE DRAFT AND DRAFT PERFORMANCE

In the last two preceding chapters, the theory for both the theoretical draft and the available draft of a chimney has been developed in detail. It has been established, first, that the theoretical draft is the difference in pressure caused by the difference in weight between the hot air or gases within the chimney and an equal column of outside air and that the intensity of the theoretical draft varies directly as the temperature of the chimney gases, the height of the chimney, and the atmospheric pressure and inversely as the outside air temperature, and the density of the chimney gases; second, that the available draft is the difference in pressure caused by the difference in weight between the hot air or gases within the chimney and an equal column of outside air less the amount of the losses in pressure due to velocity and to friction of the chimney gases, and that the intensity of the available draft varies directly as the temperature of the chimney gases, the height of the chimney, the diameter of the chimney, and the atmospheric pressure and inversely as the outside air temperature, the square of the velocity of the chimney gases, the coefficient of friction, the length of the duct, and the density of the chimney gases. The theoretical draft of a chimney is the difference in pressure expressed in inches of water when the gases in the chimney are absolutely motionless and there is no circulation whatsoever. The available draft is the difference in pressure expressed in the same manner when the gases in the chimney are flowing freely.

As stated in Chapter 1, a chimney in connection with a steam plant has two important functions or "jobs" to perform, one to help create a draft and the other to carry away the gaseous products of combustion. Hence, it may be stated in short, that the two functions of a chimney are:

1. Draft performance,
2. Capacity performance.

It is with the draft performance of a chimney that this chapter will deal.

Equation 18 gives the draft of a chimney, the theoretical draft, when the gases are absolutely motionless and the velocity of the chimney gases is equal to zero. In this case, then,

$$D_a = D_t \qquad 78$$

Equation 24 gives the draft of a chimney, the available draft, when the gases are flowing freely and the velocity of the chimney gases is equal to the average velocity of the gases going up the chimney. In this case, since the available draft is always less than the theoretical draft,

$$D_a = R_D D_t \qquad 79$$

in which R_D = ratio factor, or the relation of the available draft to the theoretical draft.

Whence $$R_D = \frac{D_a}{D_t} \qquad 80$$

The value of R_D is an extremely variable quantity and depends upon the value of the nine different factors as noted in Chapter 3. Of all of the absurd theories or statements advanced in regard to the general subject of draft, the statement that the available draft of a chimney is equal to approximately 80 per cent of the theoretical draft is perhaps the most baseless and misleading. There is no *general* relation between the available draft and the theoretical draft of a chimney. It may vary from 1 per cent, or a fraction less, to 99 per cent, or a fraction more, depending upon the conditions assumed or those to which the chimney is subjected. There are nine separate factors entering into the available draft equation, each one of which may vary from a maximum to a minimum value in the course of a year or so. It might be possible for all of the adverse conditions or factors to be a maximum and all of the favorable conditions to be a minimum at the same time, or vice versa. Again, such a condition might arise in which both the adverse conditions and the favorable conditions might be a maximum at the same time, or both might be a minimum at the same time. In any of the four cases noted above, the ratio factor would be far from 80 per cent. While these conditions may seem remote, they should be taken into consideration and the most unfavorable conditions, *on the average,* should be considered as the criterion.

The ultimate object of a thorough investigation of the draft performance of a chimney is to provide data for the accurate determination of the proper height of a chimney. As will be seen in a later chapter, unless there is sufficient and reliable data at hand for determining the *preliminary* height of a chimney, it will be impossible to obtain the proper *required* height and diameter. It is impossible to arrive at a definite conclusion from incomplete, inaccurate, or indefinite information. Furthermore, in this particular instance, an attempt to generalize on an equation derived for specific conditions is far worse than guesswork.

General equation for the available draft of a chimney

Selecting equations 18, 28 and 51 and substituting in equation 24:

$$D_a = 6.43\,H\,P_o \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right)$$

$$-\left[0.10\,W_c\,P_o\,\frac{V^2_a}{T_c} + 0.10\,f\,W_c\,P_o\,\frac{V^2_a}{T_c}\,\frac{L}{C_d}\right]$$

$$= 6.43\,H\,P_o \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right) + 0.10\,W_c\,P_o\,\frac{V^2_a}{T_c}\left(1 + \frac{f\,L}{C_d}\right) \qquad 81$$

Equation 81 gives the available draft of a chimney with all the available factors or conditions taken into consideration. Whence it will be seen that the following factors enter into the available draft and affect its intensity:

1. Outside air temperature,
2. Chimney gas temperature,
3. Height of chimney,

4. Shape of section, or value of D,
5. Velocity of chimney gases,
6. Coefficient of friction,
7. Length of duct,
8. Density of chimney gases,
9. Atmospheric pressure.

To the above should be added:

10. Volume and weight of chimney gases.

Owing to the great number of variables entering into the equation for the available draft of a chimney, it is impossible to construct a set of curves for determining its intensity graphically, as was done in the case of the theoretical draft, which can be used generally for even an average set of operating conditions. The available draft may be found without undue effort, with the aid of a slide rule, by substituting the proper values in equation 81 and reducing; or, the theoretical draft may be found from Fig. 8, the loss of draft due to velocity from Fig. 14, and the loss of draft due to friction from Fig. 20, the available draft then being the algebraic sum of these three quantities, after the proper corrections have been made.

Equation 81, however, may be reduced to a very simple form by assuming values for average working conditions for several factors, and from it a diagram can be constructed which will give the available draft of a chimney for certain assumed conditions.

Let $$P_o = P = 14.7,$$

and $$W_c = W_o = 0.08071$$

Then

$$D_a = 7.63\left(\frac{1}{T_o} - \frac{1}{T_c}\right)H - \left(0.1185\frac{V_a^2}{T_c} + 0.1185\, f\, \frac{V_a^2}{T_c}\frac{L}{C_d}\right) \tag{82}$$

$$= 7.63\left(\frac{1}{T_o} - \frac{1}{T_c}\right)H - 0.1185\frac{V_a^2}{T_c}\left(1 + f\frac{L}{C_d}\right) \tag{83}$$

Now assuming an outside air temperature of 60 deg. Fahr., a chimney gas temperature of 600 deg., and a coefficient of friction of 0.016,

$$D_a = 0.00748\, H - 0.0001118\, V_a^2\, K_h \tag{84}$$

In equation 84, the first term of the right hand member is the theoretical draft reduced to its simplest form, and the second term the combined loss of draft due to velocity and friction also reduced to its simplest form, both based on the same operating conditions.

Let $h_{vf} = 0.0001118\, V_a^2\, K_h$ 85

in which $K_h = 1 + f\dfrac{L}{C_d}$

Then $D_a = 0.00748\, H - h_{vf}$ 86

Fig. 27 gives the value of h_{vf} for various values of V and K_h, based on a chimney gas temperature of 600 deg. Fahr., a chimney gas density of 0.08071 lbs. per cu. ft. at 32 deg. Fahr., coefficient of friction of 0.016, standard atmospheric pressure, and a circular, octagonal, or square section.

Fig. 28 gives the available draft of a chimney for various values of H and h_{vf}, based on the same conditions as noted above, and in addition an outside air temperature of 60 deg. Fahr.

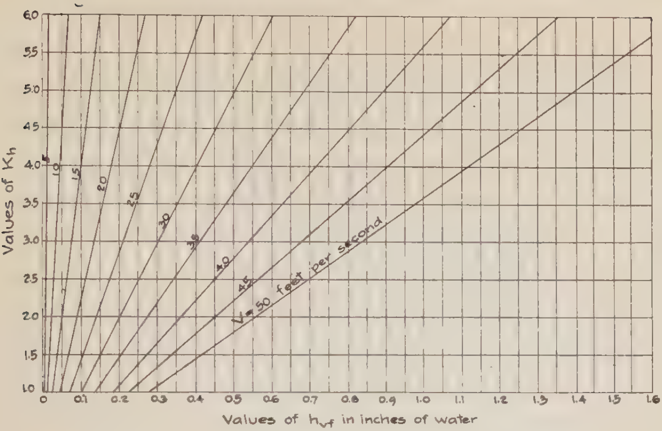

Fig. 27. Values of h_{vf} in Equation $h_{vf} = .0001118\ V^2_a K_h$. Based on $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $P_o = P = 14.7$ lbs. per sq. in., and circular, octagonal, or square sections.

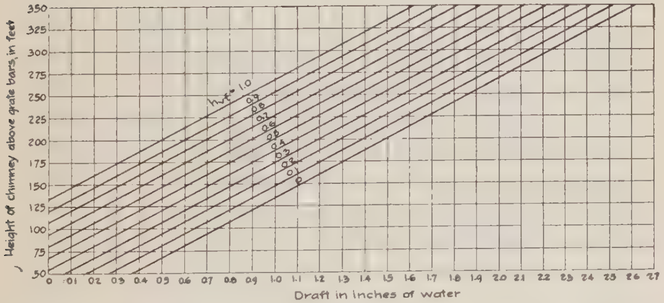

Fig. 28. Available Draft of Chimneys for Various Values of H and h_{vf}.

Based on $t_o = 60$ deg. F., $W_c = 0.08071$, $f = 0.016$, $P_o = P = 14.7$ lbs. per sq. in., and circular, octagonal, or square sections.

Based on the volume of the chimney gases, the available draft is equal to

$$D_a = 0.00748\,H - 0.0001118\,\frac{Q^2}{A^2}\,K_h \tag{87}$$

Based on the weight of the chimney gases discharged, the available draft is equal to

$$D_a = 0.00748\,H - 0.0798\,\frac{W^2_a}{A^2}\,K_h \tag{88}$$

For a chimney with a circular section, equation 88 reduces to

$$D_a = 0.00748\,H - 0.1297\,\frac{W^2_a}{D^4}\,K_h \tag{89}$$

Equation 89 gives the available draft of a chimney in its simplest and most convenient form, under the conditions as assumed and noted. As stated heretofore, the first term of the right hand member is the theoretical draft reduced to its simplest form and the second term, the combined loss due to velocity and to friction also reduced to its simplest form. This equation will now be used as a basis for investigating the draft performance of a chimney and also for determining the ratio factor between the available draft and the theoretical draft.

Assuming, for example, a height (H) of 100 ft. and L = H,

$$D_a = 0.748 - 0.1297\,\frac{W^2_a}{D^4}\left(1 + \frac{6.4}{D}\right) \tag{90}$$

Table 8 gives the equations for the available draft of a chimney for various heights of chimney under the specific conditions as assumed and noted

TABLE 8

AVAILABLE DRAFT EQUATIONS FOR VARIOUS HEIGHTS OF CHIMNEY

H	D_a	Equation No.
80′0″	$0.598 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{5.12}{D}\right)$	91
100′0″	$0.748 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{6.4}{D}\right)$	90
125′0″	$0.935 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{8.0}{D}\right)$	92
150′0″	$1.122 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{9.6}{D}\right)$	93
175′0″	$1.309 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{11.2}{D}\right)$	94
200′0″	$1.496 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{12.8}{D}\right)$	95
225′0″	$1.683 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{14.4}{D}\right)$	96
250′0″	$1.870 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{16.0}{D}\right)$	97
275′0″	$2.057 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{17.6}{D}\right)$	98
300′0″	$2.244 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{19.2}{D}\right)$	99
325′0″	$2.431 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{20.8}{D}\right)$	100
350′0″	$2.618 - 0.1297 \frac{W^2_a}{D^4}\left(1 + \frac{22.4}{D}\right)$	101

heretofore. Figs. 29 to 36 give the available draft of chimneys of various heights (H) for various diameters and weights of chimney gases discharged. These figures are of extreme importance and should be used with care and discretion. They are based on a circular section of chimney, an outside air temperature of 60 deg. Fahr., a chimney gas temperature of 600 deg. Fahr., a chimney gas density of 0.08071 lbs. per cu. ft. at 32 deg. Fahr., a coefficient of friction of 0.016, length of duct equal to height of chimney ($L = H$), and standard atmospheric pressure ($P_o = P = 14.7$ lbs. per sq. in.).

Each of these sets of curves follows the same general scheme and shows that the available draft is a maximum and is equal to the theoretical draft in intensity when no gases are flowing, and also that the available draft increases as the diameter of the chimney, and decreases as the quantity of chimney gases increases. As will be seen later when the subject of the ratio factors is taken up, the available draft as given by Figs. 29 to 36 varies directly as the temperature of the chimney gases and the atmospheric pressure, and inversely as the temperature of the outside air, the coefficient of friction, the length of the duct, and the density of the chimney gases.

In the final analysis, the available draft of a chimney should be based only upon the weight of the chimney gases discharged by the chimney. The actual amount of gases generated in a boiler furnace is known or can be computed accurately and these gases must of necessity pass on through the boiler and then out into the chimney itself. Unless there are leakages in the installation, of which there is no necessity whatsoever, the amount of gases passing up the chimney is the same as the amount coming from the boiler. If the available draft were based on the velocity of the chimney gases, it would be necessary to determine the velocity of the latter by means of an anemometer, but velocities so determined are relative values only. It is known that the velocity of the chimney gases varies greatly at any cross section of the chimney, being greater in the center than near the surface of the shaft where the effect of friction is greatest, and in order to secure an average value it

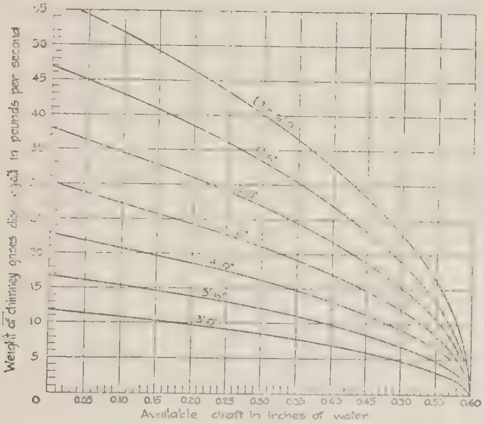

Fig. 29. Available Draft of Chimneys for H = 80 ft.
Circular Section
Based on $t_o = 60$ deg. F., $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $L = H$, and $P_o = P = 14.7$ lbs. per sq. in.

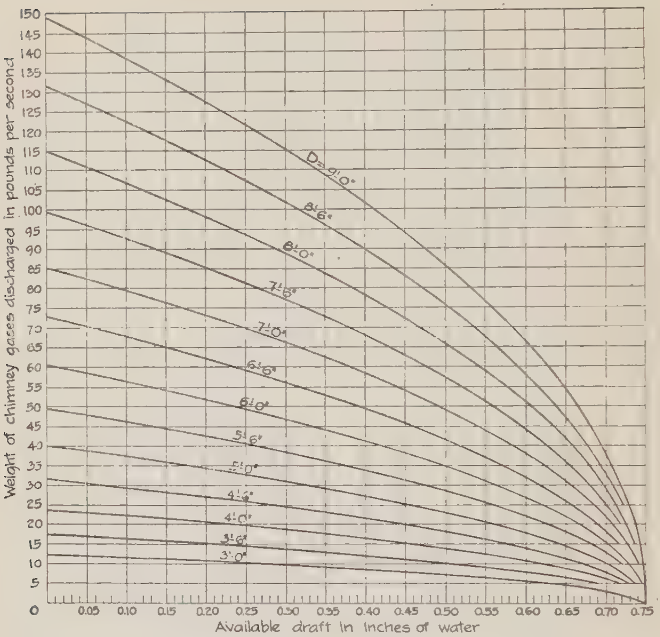

Fig. 30. Available Draft of Chimneys for H = 100 ft.
Circular Section

Based on $t_o = 60$ deg. F., $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $L = H$, and $P_o = P = 14.7$ lbs. per sq. in.

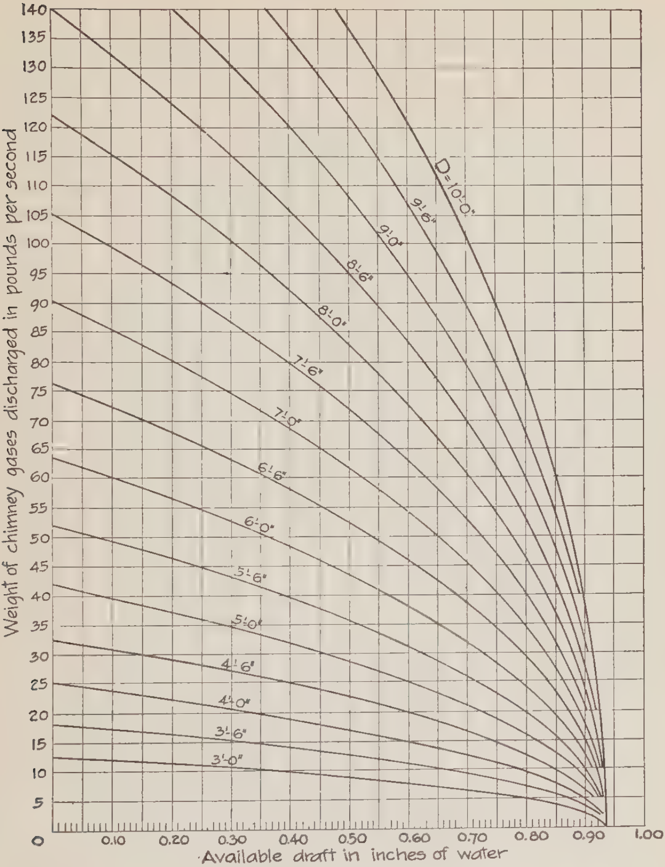

Fig. 31. Available Draft of Chimneys for H = 125 ft.
Circular Section

Based on $t_o = 60$ deg. F., $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $L = H$, and $P_o = P = 14.7$ lbs. per sq. in.

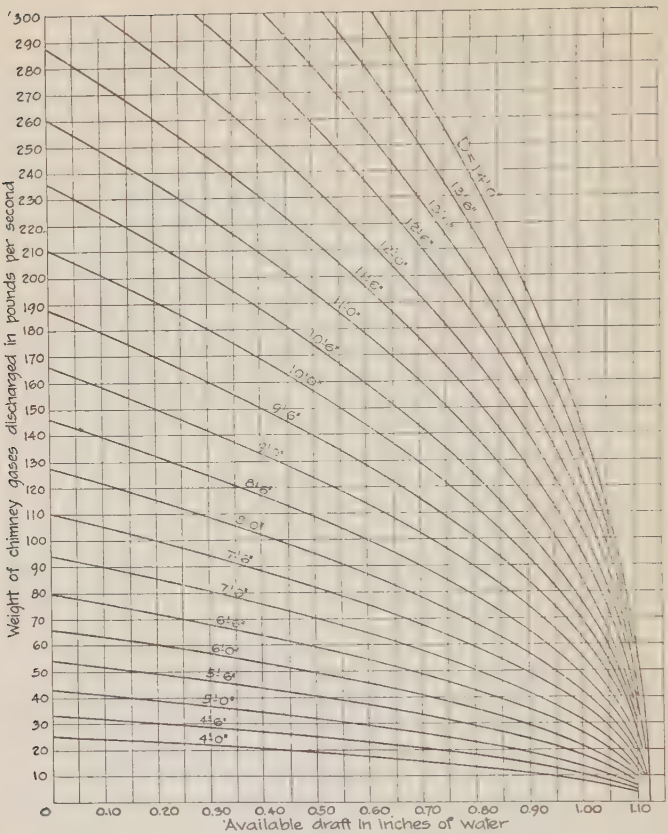

Fig. 32. Available Draft of Chimneys for H = 150 ft.

Circular Section

Based on $t_0 = 60$ deg. F., $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $L = H$, and $P_0 = P = 14.7$ lbs. per sq. in.

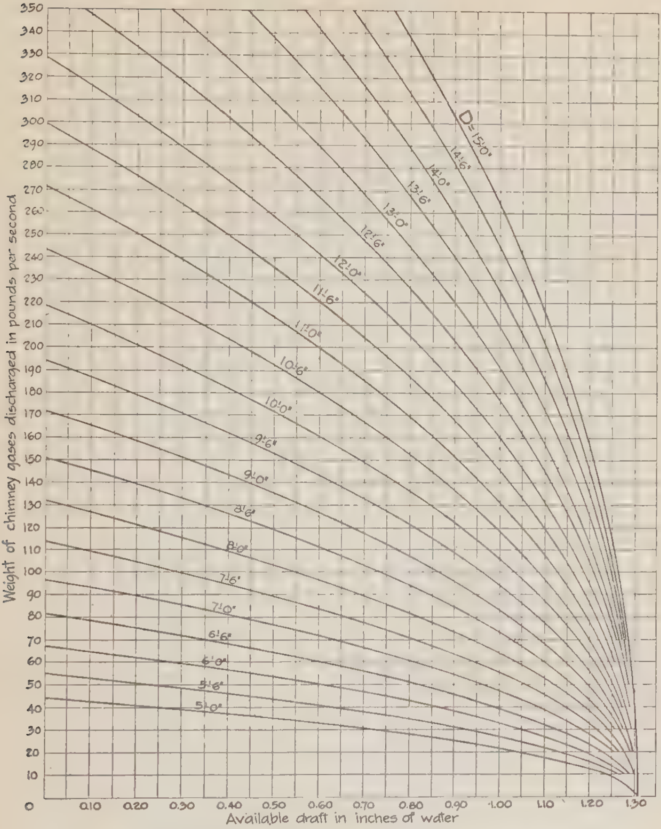

Fig. 33. Available Draft of Chimneys for H = 175 ft.

Circular Section

Based on $t_o = 60$ deg. F., $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $L = H$, and $P_o = P = 14.7$ lbs. per sq. in.

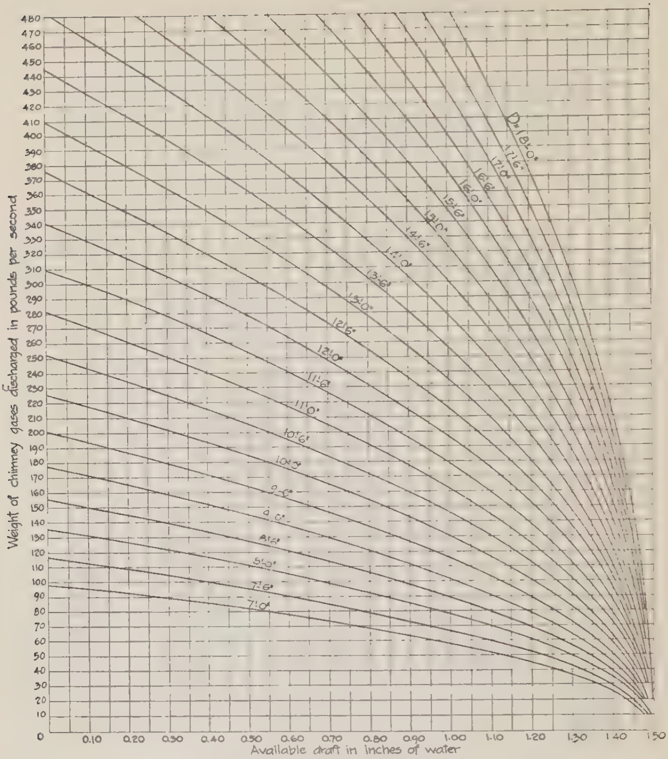

Fig. 34. Available Draft of Chimneys for H = 200 ft.

Circular Section

Based on $t_o = 60$ deg. F., $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $L = H$, and $P_o = P = 14.7$ lbs. per sq. in.

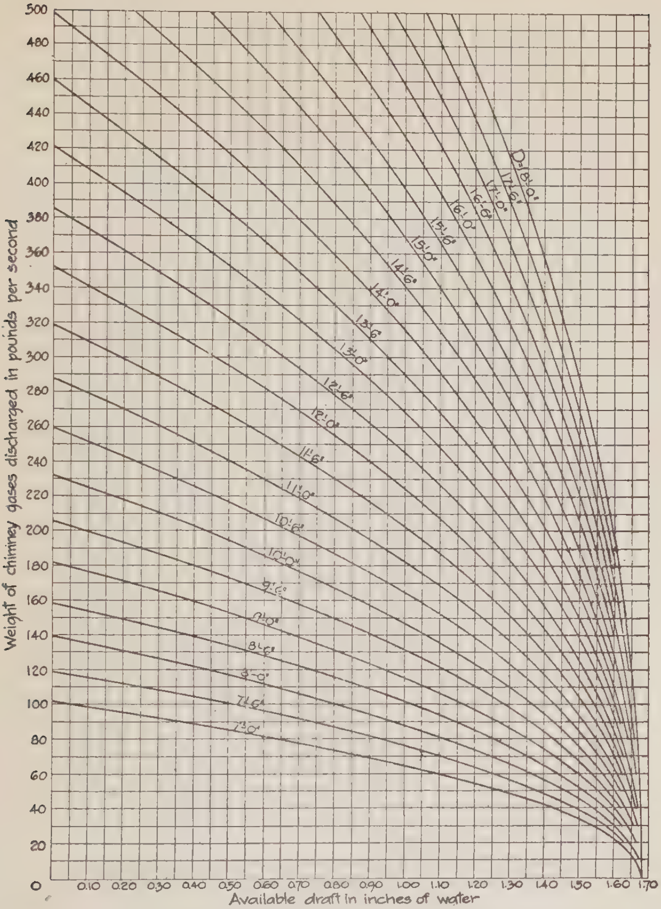

Fig. 35. Available Draft of Chimneys for H = 225 ft.

Circular Section

Based on $t_o = 60$ deg. F., $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $L = H$, and $P_o = P = 14.7$ lbs. per sq. in.

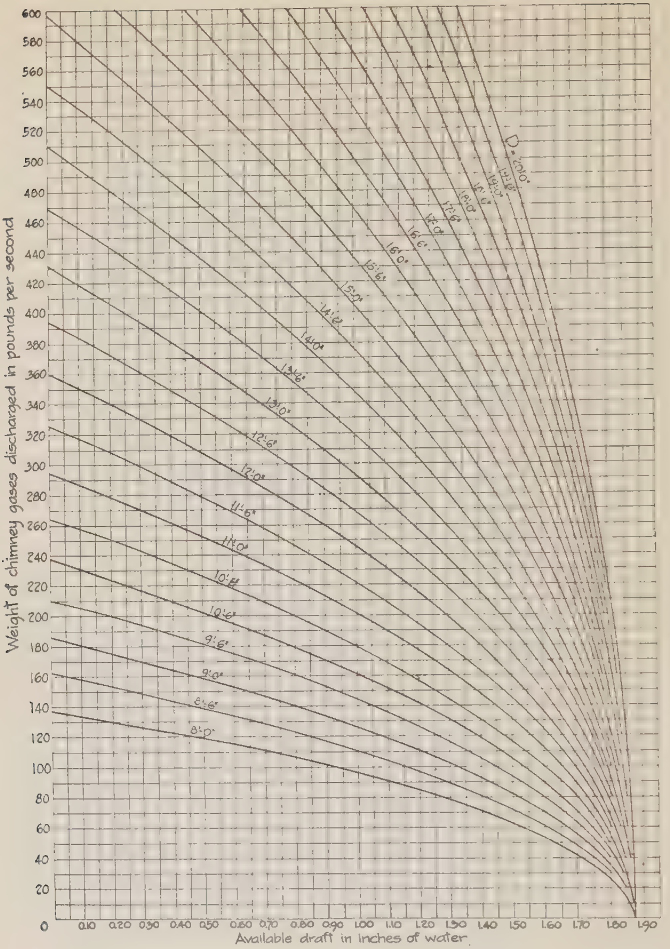

Fig. 36. Available Draft of Chimneys for H = 250 ft.
Circular Section

Based on $t_o = 60$ deg. F., $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $L = H$, and $P_o = P = 14.7$ lbs. per sq. in.

would be necessary to take simultaneous readings at several different points at the same level or cross section. In the case of working chimneys and those being built at the present day, this would be a practical impossibility since no provision is made in the shaft for an operation of this character. Likewise, if the available draft were based on the volume of the chimney gases, it again would be necessary to determine the average velocity by some mechanical means.

Example: Determine the available draft of a chimney 200 ft. high by 10 ft. inside diameter under the conditions as assumed in developing equation 95, and for the following data:

Analysis of coal: 79 per cent carbon,
5 per cent total hydrogen,
2 per cent oxygen,
2 per cent nitrogen,
3 per cent sulphur,
9 per cent ash.

$G = 1000$ square feet of grate surface,
$C_g = 25$ pounds of coal per square foot of grate surface per hour.

Now the theoretical weight of air required to burn one pound of coal is equal to

$$11.52 \times 0.79 + 34.56 \left(0.05 - \frac{0.02}{8}\right) + 4.32 \times 0.03 = 9.10 + 1.64 + 0.13 = 10.87 \text{ lbs.}$$

The total weight of the products of combustion per pound of coal equals

$$10.87 + 0.79 + 0.0475 + 0.03 = 11.74 \text{ lbs.}$$

The total weight of the products of combustion equals

$$1000 \times 25 \times 11.74 = 293{,}500 \text{ lbs. per hour,}$$

$$W_a = \frac{293{,}500}{3600} = 81.5 \text{ lbs. per second}$$

Substituting in equation 95 and reducing:

$$D_a = 1.496 - 0.1297 \frac{(81.5)^2}{(10)^4} \left(1 + \frac{12.8}{10}\right)$$

$$= 1.496 - 0.196$$

$$= 1.300 \text{ inches of water.}$$

The above analysis is based on the actual amount of air required. If 50 per cent excess air is used, the total weight of the products of combustion per pound of fuel is equal to

$$(10.87 + 5.43) + 0.79 + 0.0475 + 0.03 = 17.17 \text{ lbs.}$$

Whence, the total weight of the products of combustion is equal to

$$1000 \times 25 \times 17.17 = 429{,}250 \text{ lbs. per hour}$$

or $$W = \frac{429{,}250}{3600} = 119.2 \text{ lbs. per second.}$$

Finally, the available draft is equal to

$$D_a = 1.496 - 0.1297 \frac{(119.2)^2}{(10)^4} \left(1 + \frac{12.8}{10}\right)$$

$$= 1.496 - 0.420$$

$$= 1.076 \text{ inches of water.}$$

Determine the available draft of a chimney 150 ft. high by 6 ft. inside diameter under the conditions as assumed in developing equation 93, and for the following data:

Analysis of flue gases: 9.5 per cent CO_2,
10.7 per cent O,
0.5 per cent CO,
79.3 per cent N
(by difference)

$G = 325$ sq. ft. of grate surface,
$C_g = 20$ lbs. of coal per sq. ft. of grate surface per hour.

Assume 3.0 per cent sulphur, by weight,
76.8 per cent total carbon in fuel, by weight.

$$W_{tp} = \left(\frac{11 \times 9.5 + 8 \times 10.7 + 7\ (0.5 + 79.3)}{3\ (9.5 + 0.5)}\right) 0.768 + \frac{0.03}{1.83}$$

$$= \left(\frac{104.5 + 85.6 + 558.6}{30}\right) \times 0.768 + 0.02$$

$$= 19.19 \text{ lbs. of gas per pound of fuel.}$$

Whence, the total weight of the products of combustion equals

$$325 \times 20 \times 19.19 = 124{,}375 \text{ lbs. per hour}$$

or $$W = \frac{124{,}375}{3600} = 34.5 \text{ lbs. per sec.}$$

Substituting in equation 93 and reducing:

$$D_a = 1.122 - 0.1291\ \frac{(34.5)^2}{(6)^4}\left(1 + \frac{9.6}{6}\right)$$

$$= 1.122 - 0.308$$

$$= 0.814 \text{ inches of water.}$$

After the total weight of the products of combustion or the amount of gases passing up or discharged by the chimney, per second, has been found, the available draft may be found directly from Fig. 32 for the 150 ft. x 6 ft. chimney, and from Fig. 34 for the 200 ft. x 10 ft. chimney.

Too much attention cannot be drawn to the fact that the equations in Table 8 and also the curves as shown by Figs. 29 to 36 are based on definite and specific operating conditions, and that any deviation from these specified conditions will effect the intensity of the available draft. All other factors or conditions remaining constant, the intensity of the available draft will decrease if the temperature of the outside air increases, increase if the temperature of the chimney gases increases, increase if the coefficient of friction decreases, decrease if the density of the chimney gases increases, increase if the length of the duct decreases, and decrease if the atmospheric pressure decreases. An inspection of the curves will show that the intensity of the available draft will increase if the height of the chimney increases, increase if the diameter of the chimney increases, and decrease if the weight of the chimney gases discharged by the chimney increases. In view of the above facts, the equations and curves as noted should be used with extreme care if accuracy is desired and the proper corrections should be applied when and where necessary.

The usual expression for the available draft of a chimney as given by several writers is as follows:

$$D_a = K_D H - \frac{f W^2_a C H}{A^3} \qquad 102$$

in which f = 0.0020 for brick lined chimneys; temperature of chimney gases 600 deg. Fahr.,

$= 0.0015$ for brick lined chimneys; temperature of chimney gases 350 deg. Fahr.,
$= 0.0015$ for steel chimneys; temperature of chimney gases 600 deg. Fahr.,
$= 0.0011$ for steel chimneys; temperature of chimney gases 350 deg. Fahr.

The symbol f in the above equation does not represent the coefficient of friction, but is the product of several reduction factors, and is based on standard atmospheric pressure. No mention is made, however, of the assumed temperature of the outside air, the density of the chimney gases, the length of the duct, or the actual coefficient of friction.

Assuming a circular section of chimney and f = 0.0020:

$$D_a = K_D\ H - 0.013 \frac{W_a^2\ H}{D^5} \qquad 103$$

Using the same data as was used in determining the available draft in the first example noted heretofore:

$$D_a = 0.00748 \times 200 - 0.013\ \frac{(81.5)^2 \times 200}{(10)^5}$$

$$= 1.496 - 0.173$$

$$= 1.323 \text{ inches of water.}$$

In the second example:

$$D_a = 0.00748 \times 150 - 0.013\ \frac{(34.5)^2 \times 150}{(6)^5}$$

$$= 1.122 - 0.300$$

$$= 0.822 \text{ inches of water.}$$

The results as obtained from equation 102 correspond closely with those as obtained from equations 93 and 95. Equations 102 and 103, however, are incomplete in that they do not include the loss of draft due to velocity and as a consequence the results as obtained by these two equations are actually less than those obtained by the equations given in Table 8. An average result for the loss of draft due to friction is 0.10 inches of water as given by a chimney gas velocity of 30 ft. per sec. and a chimney gas temperature of 600 deg. Fahr. In this case then, the results as given by the term representing the loss due to friction in equation 102 are excessive. The loss of draft due to velocity cannot be expressed as a relative loss to the loss due to friction due to the fact that the height and diameter of the chimney affect the latter while neither one has an influence on the former.

Following the idea as expressed by equation 102, the equation for the available draft of a chimney may be somewhat simplified by separating the term representing the loss due to velocity and combining the term representing the loss due to friction with the term for the theoretical draft. From equations 18, 51, and 28.

$$D_a = 7.63\,H\left(\frac{1}{T_o} - \frac{1}{T_c}\right) - 0.1185\,f\,\frac{V^2}{T_c}\,\frac{L}{C_r} - 0.1185\,\frac{V^2}{T_c} \qquad 104$$

Assuming an outside air temperature of 60 deg. Fahr., a chimney gas temperature of 600 deg. Fahr., a coefficient of friction of 0.016, and a circular section, the available draft based on the weight of the chimney gases is equal to

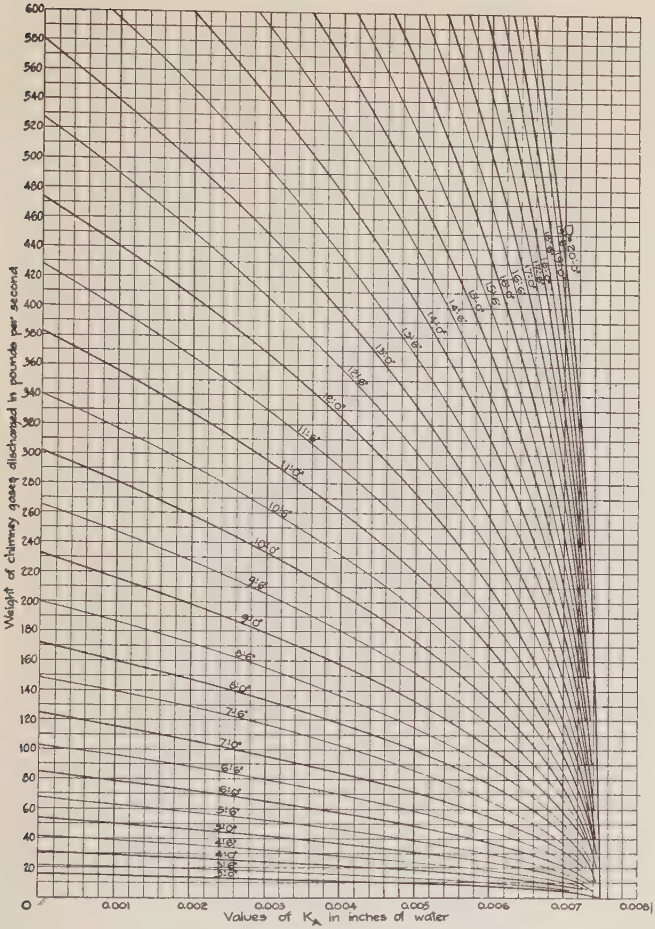

Fig. 37. Values of K_A in Equation $K_A = 0.00748 - 0.00826 \dfrac{W^2_a}{D^5}$

Based on $t_o = 60$ deg. F., $t_c = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $L = H$, and $P_o = P = 14.7$ lbs. per sq. in.

$$D_a = \left(0.00748\ H - 0.00826\ \frac{W_a^2\ L}{D^5}\right) - 0.1297\ \frac{W_a^2}{D^4} \tag{105}$$

If L = H, then

$$D_a = H\ \left(0.00748 - 0.00826\ \frac{W_a^2}{D^5}\right) - 0.1297\ \frac{W_a^2}{D^4} \tag{106}$$

$$= H\ K_A - h_v \tag{107}$$

in which $$K_A = 0.00748 - 0.00826\ \frac{W_a^2}{D^5} \tag{108}$$

Fig. 37 gives the values for K_A for various values of W and D. Values for h_v may be found from Fig. 18.

Example: Determine from equation 106, and also from Figs. 37 and 18, the available draft for the conditions as noted in the first example as given heretofore.

Substituting in equation 106:

$$D_a = 200\ \left(0.00748 - 0.00826\ \frac{(81.5)^2}{(10)^5}\right) - 0.1297\ \frac{(81.5)^2}{(10)^4}$$

$$= 200 \times 0.00693 - 0.086$$

$$= 1.300 \text{ inches of water.}$$

From Fig. 37, K_A for W = 81.5 and D = 10 ft. is equal to 0.0069.

From Fig. 18, h_v for W = 81.5 and D = 10 ft. is equal to 0.08.

Whence $D_a = 200 \times 0.0069 - 0.08 = 1.30$ in. of water.

CHAPTER V

REQUIRED DRAFT AND GENERAL DRAFT EQUATION

Heretofore, in the discussion of draft, the theory has been developed on the assumption that the chimney stood by itself alone and was not connected to a boiler. A difference in temperature between the hot gases within the chimney and the cooler outside air produces a difference in pressure which is designated by the term *theoretical draft* and which is a maximum under any condition when the gases within the chimney are absolutely motionless. When the gases are flowing freely, however, the intensity of the difference in pressure, or the theoretical draft, is decreased by the losses due to velocity and to friction. This reduced difference in pressure is designated by the term *available draft.* Let it now be assumed that the chimney is connected directly to a steam boiler and that the outside air enters the boiler through the ash-pit entrance or air inlet, passes through the grates and the fuel bed where the hot gases are formed; and the hot gases in turn pass on through the boiler, the breeching, the turns in the breeching and finally out into the chimney itself where they are carried to the upper regions.

If, in such an installation, draft observations are made along the path of the air and gases between the air inlet and the chimney, it will be found that they will become less the farther from the chimney they are taken until at the ash-pit entrance there will be no perceptible change in the reading. These differences in the draft-gauge readings are due to the retardation of the gases offered by the grates, fuel bed, boiler and baffles, breeching, and turns in the breeching, and represent the equivalent pressure or draft necessary to "pull" or "push," as the case may be, the gases past or through these obstructions. They are designated by the terms "loss of draft," "loss of pressure," "pressure head," or "loss of head," the first being the most common of all.

Figs. 1 and 2 show typical draft-gauge readings in a steam power plant installation. Draft readings may be taken at any point along the path of the gases and a loss of draft will be noted between any two points. This loss of draft represents the difference in pressure required to force the air or gases from one point to the other. The greatest loss of draft in an average installation is that through the fuel bed, and represents the amount of draft necessary to force the required amount of air necessary for combustion through the fuel bed. This loss is measured by taking a reading below and another above the fuel bed and noting the difference between the two readings. The next greatest loss is that through the boiler, and this is measured by taking one reading at the ash-pit entrance or air inlet and another at the breeching entrance, and noting the difference between the two. The loss through the breeching is measured by taking a reading at the junction of the breeching with the chimney and another at the junction of the breeching with the boiler or boilers, and noting the difference between the two. The loss through the breeching includes the loss due to the bends in the breeching when an observation is made but in making theoretical assumptions a separate value is assigned to each. The loss of draft through the chimney itself, due to velocity and to friction, is measured by taking a reading at the bottom of the breeching opening and another at the top of the chimney and noting the difference between the two. As stated heretofore, the loss of draft due to velocity and the loss due to friction in the chimney are observed as one loss since the two cannot be separated. In theory, however, separate calculations are made for each loss.

The sum of all of these various observed losses of draft should in no case exceed the theoretical draft of the chimney.

General Draft Equation

The general equation for draft in a steam boiler plant is expressed as follows:

$$D_t - (h_v + h_f) = h_F + h_B + h_{Br} + h_T + h_D \qquad 109$$

in which D_t = theoretical draft,
h_v = loss of draft due to velocity of the chimney gases,
h_f = loss of draft due to friction of the chimney gases,
h_F = loss of draft through the fuel bed,
h_B = loss of draft through the boiler,

h_{Br} = loss of draft through the breeching,
h_T = loss of draft due to turns or bends,
h_D = loss of draft due to damper friction.

To the above may be added:

h_E = loss of draft through the economizer when the latter is not a part of the boiler, or is not included in the loss through the boiler,
h_O = loss of draft due to sudden enlargement of an opening, or a section.

All of the above losses of draft are expressed in inches of water.

In equation 109:

D_t = *theoretical* draft in inches of water, as before,
$D_t - (h_v + h_f)$ = *available* draft in inches of water, as before,
$h_F + h_B + h_{Br} + h_T + h_D$ = *required* draft in inches of water.

Loss of Draft through the Fuel Bed

The loss of draft through the fuel bed, h_F, or the amount of draft required to effect a given or required rate of combustion varies between wide limits and represents from 40 to 75 per cent of the total loss of draft throughout the entire installation. In coal-fired plants, the loss of draft through the fuel bed is dependent upon the following factors, viz:

1. Character and condition of the fuel,
2. Amount of fuel burned per square foot of grate surface per hour, or the rate of combustion,
3. Percentage of ash in the fuel,
4. Volume of interstices in the fuel,
5. Thickness of the fuel bed.

There is a certain intensity of draft with which the best results will be obtained for each and every kind of coal and rate of combustion and this intensity of draft can be found only by experiment. The curves shown in Fig. 38 have been plotted from the results of numerous tests and experiments in actual operation and give the intensity of draft necessary to burn properly several kinds of coal at various rates of combustion, or the amount of draft necessary to force the required amount of air through the fuel bed. It will be seen that the amount of draft increases as the percentage of volatile matter diminishes and the percentage of fixed carbon increases, being comparatively low for the lower grades of bituminous coals and highest for the high grades and small sizes of anthracites. Also, when the interstices of the coal are large and the particles of coal are not well broken up, as with the bituminous coals, much less draft is required than when the particles are small and are well broken up as with the bituminous slack and the small sizes of anthracites.

In general, the loss of draft through the fuel bed increases as follows:

1. The percentage of volatile matter diminishes,
2. The percentage of fixed carbon increases,
3. The thickness of the fire increases,
4. The percentage of the ash increases,
5. The volume of the interstices diminish.

Insufficient draft will cause the coal to accumulate on the grates, the result being a dead and smoky fire and consequently poor combustion. If there is an excess of draft, the fuel will be rapidly consumed on parts of the grate, thus leaving the fire thin in spots and resulting in losses due to an excess of air. It is therefore of great importance that the draft be regulated properly for every kind of coal.

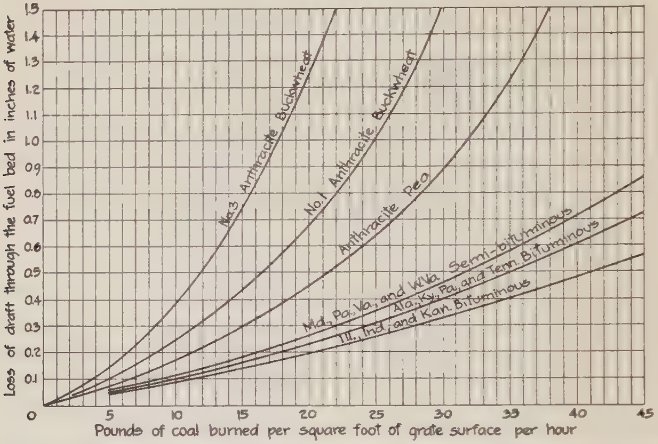

Fig. 38. Draft Required at Different Rates of Combustion for Various Kinds of Coal.

Specific requirements for the amount of draft necessary to burn the various kinds and grades of coal at various rates of combustion in stoker-fired installations should be obtained from the stoker manufacturer.

A thorough analysis should be made of the coal that is expected to be burned so that proper assumptions may be made as to the amount of draft required. Under ordinary conditions, 0.01 inches of water natural draft is equivalent to about eight feet of height of the chimney. A difference of one or two tenths inches of water in the assumption of the loss of draft through the fuel bed might mean the loss of several feet of chimney that is required. It is quite likely that much of the trouble in operation in some plants may be traced to the fact that wrong assumptions have been made as to the loss through the fuel bed. Of all the factors entering into the loss of draft through the installation, that through the fuel bed is the only one which cannot be accurately determined beforehand, unless the kind of coal which is to be burned is known.

In making the preliminary assumption for the loss of draft through the fuel bed, due allowances should be made for a variation in the grade of fuel to be burned and also in the rate of combustion. For example, assume that the coal to be burned is a low grade bituminous mine-run and that the rate of combustion is 25 lbs. per sq. ft. of grate surface per hour. In this case, the draft loss through the fuel bed is equal to 0.25 inches of water as given by Fig. 38. Now, when the coal is changed to a high grade semi-bituminous slack with the same rate of combustion, the loss of draft will be equal to 0.35 inches of water, or more than 40 per cent more than the former.

Again, assume a semi-bituminous mine-run coal with a rate of combustion of 20 lbs. per sq. ft. of grate surface per hour. The loss of draft in this case is equal to 0.27 inches of water. Assuming that the same grade of coal is used, but that the rate of combustion is increased to 35 lbs. per sq. ft. of grate surface per hour, the loss of draft will be equal to 0.55 inches of water, or about 57 per cent more than the former.

It is usually better to have too much draft than an insufficient amount, but this is not always true. The draft may be sufficient for a certain kind of coal but insufficient for another kind, as noted heretofore. If there is an excess of draft, it may be controlled by means of a damper, but if there is an insufficient amount nothing can be done to increase it except to increase the height of the chimney—which is seldom possible—or to provide more pressure by means of a fan. Both in this particular case, are makeshifts.

In powdered-fuel and oil-fired installations, there will be no loss of draft through the fuel bed and consequently this factor can be neglected. All other things being equal, the height of the chimney in installations of this character will be less than the height of the chimney for coal-fired installations.

Loss of Draft through the Boiler

The loss of draft through the boiler, h_B, also varies between wide limits and depends upon the following factors:

1. Type of boiler,
2. Size of boiler,
3. Rate of operation,
4. Arrangement of tubes,
5. Arrangement of baffles,

6. Type of grate,
7. Design of brickwork setting,
8. Excess air admitted,
9. Location of entrance into breeching.

Curves showing the loss of draft through the boiler are based on the load, or quantity of gases passing through the boiler, expressed in terms of percentage of the ordinary rating, or rate of operation. Owing to the large number of boilers of different designs and the great variety of baffle arrangements, it is impossible to give a set of curves for the loss of draft through the boiler which can be used generally. It is therefore advisable to secure this information from the manufacturer of the particular type of boiler and baffle arrangement under consideration. Fig. 39 gives a few curves showing the loss of draft through several makes of boilers at various ratings. These curves should be used only in preliminary assumptions and calculations, since they may represent values far from the actual loss of draft through the boiler which will actually be used.

It is extremely important that accurate and reliable information be obtained on the loss of draft through the boiler. After the type of boiler to be used and also the maximum rate at which it will be operated have been decided upon, a value of the loss of draft through the boiler should be selected which will represent the maximum loss when the boiler is operated at the maximum rate of operation. For example, if the loss of draft through a boiler is 0.40 inches of water when it is operated at its normal rating and 0.70 inches of water when it is operated at 250 per cent of its rated capacity, the latter figure should be used as the loss of draft through the boiler. It is assumed, of course, that 250 per cent represents the maximum rate at which the boiler will ever be operated. In case the boiler is to be operated at a still higher rate, the loss of draft then will be still greater. This factor is of extreme importance, as many mistakes have been made by assuming the loss of draft through

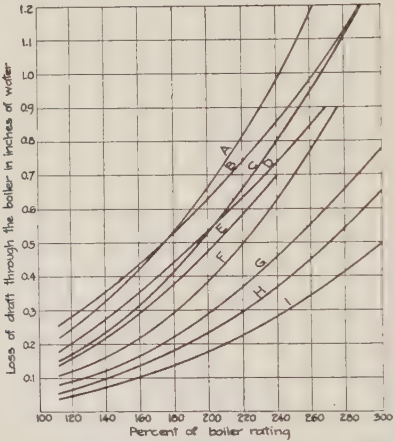

Fig. 39. Loss of Draft through the Boiler.

A—4 pass, vertical baffle, 14 tubes high.
B—5 pass, vertical baffle, 16 tubes high.
C—4 pass, diagonal baffle, 14 tubes high.
D—3 pass, vertical baffle, 16 tubes high.
E—3 pass, vertical baffle, 14 tubes high.
F—3 pass, vertical baffle, 12 tubes high.
G—3 pass, diagonal baffle, 14 tubes high.
H—3 pass diagonal baffle, 16 tubes high.
I—3 pass, diagonal baffle, 18 tubes high.

the boiler at a figure which represents the loss when the boiler is operated at only its normal rating.

When a boiler is installed and in operation, the loss of draft depends upon the amount of gases flowing through the boiler. This in turn depends upon the proportion of excess air admitted for combustion. The amount of excess air is measured by the CO_2 content in the gases; the less the amount of CO_2, the greater the amount of excess air, and hence the greater the loss of draft through the boiler.

If the proportion of excess air and the temperature of the flue gases remain constant, the loss of draft through the boiler will vary as the square of the velocity of the gases, or as the square of the load, so that at 200 per cent of rating, for example, the loss of draft will be four times the loss at 100 per cent of rating. With natural draft, however, the loss will sometimes increase faster than as the square of the load or rating, since the proportion of excess air increases with the increased vacuum in the combustion chamber. With forced draft, on the other hand, the proportion of excess air is much less and consequently the loss of draft will increase at a lower rate than the square of the rating.

The loss of draft through the boiler will vary directly as the size of the boiler and the length of the gas passages within. The loss also varies as the number of tubes high but not in a direct ratio, inasmuch as the loss due to the reversal of flow at the ends of the baffles remains constant regardless of the height of the boiler. The arrangement of the tubes, whether the gases flow parallel with, or at right angles to, the tubes, has an appreciable effect. The arrangement of the baffles influences the loss greatly, the loss of draft through a boiler with five passes being greater than the loss through one of four passes. A poor design and a rough condition of the brickwork will increase the loss greatly, whereas a proper design and a smooth condition of the brickwork will decrease the loss. The loss through the boiler will be less when the breeching entrance is located at or near the top of the boiler than when it is located at or near the bottom since the gases have a shorter distance to travel in the former case.

Loss of Draft through the Breeching

The loss of draft through the breeching, or the loss due to friction between the flue gases and the interior walls of the breeching, h_{Br}, may be determined from equation 51:

$$h_{Br} = 0.10\ f\ W_c\ P_o\ \frac{V^2_a}{T_c}\ \frac{l}{C_{br}} \qquad 110$$

In which h_{Br} = loss of draft through the breeching in inches of water
l = length of breeching in feet
C_{br} = hydraulic radius of section

$$\text{Since } C_{br} = \frac{A}{C}$$

$$\text{Then } h_{Br} = 0.10\ f\ W_c\ P_o\ \frac{l}{T_c}\ \frac{C}{A}\ V^2_a \qquad 111$$

Most breechings are built rectangular in section. Whence, for a rectangular section:

$$C_{br} = \frac{A}{C} = \frac{D_{br}\ H_{br}}{2(D_{br} + H_{br})} \tag{112}$$

in which D_{br} = width of breeching in feet,

H_{br} = height of breeching in feet.

It is quite convenient to express the relation between the height and width of the breeching in the form of a ratio. For example, for a breeching with a height equal to twice the width, the relation is expressed as a ratio of sides of 2:1; for a height equal to three times the width, 3:1; and so on. Most breechings are built with a height equal to twice the width and in this case since

$$H_{br} = 2\ D_{br}$$

and

$$C_{br} = \frac{D_{br} \times 2\ D_{br}}{2(D_{br} + 2\ D_{br})} = \frac{D_{br}}{3} \tag{113}$$

Substituting in equation 110 and reducing:

$$h_{Br} = 0.30\ f\ W_c\ P_o\ \frac{V^2_s}{T_c}\ \frac{1}{D_{br}} \tag{114}$$

Since the inside surface of all breechings, in time, becomes covered with a coat of soot, the value of f doubtless is the same as that for chimneys and for $P_o = P = 14.7$ and $W_c = 0.08071$:

$$h_{Br} = 0.00568\ \frac{V^2_s}{T_c}\ \frac{1}{D_{br}} \tag{115}$$

Based on the volume of flue gases passing through the breeching, equation 110 becomes

$$h_{Br} = 0.10\ f\ W_c\ P_o\ \frac{Q^2}{A^2\ T_c}\ \frac{1}{C_{br}} \tag{116}$$

Based on the weight of the flue gases passing through the breeching, equation 110 becomes

$$h_{Br} = 0.0000893\, f\, \frac{W^2_a\, T_c\, l\, C}{P_o\, A^3\, W_c} \qquad 117$$

For $f = 0.016$, $W_c = 0.08071$, $P_o = P = 14.7$ and $l = 1$ foot, equation 110, for a 2:1 rectangular section becomes:

$$h_{Br} = 0.000955\, \frac{W^2_a}{D^5_{br}} \qquad 118$$

Equation 118 gives the loss of draft through the breeching per foot of duct in its simplest form, and is based on a flue gas temperature of 600 degrees Fahr., a flue gas density of 0.08071 pounds per cu. ft. at 32 deg. Fahr., coefficient of friction of 0.016, standard atmospheric pressure, and ratio of sides of 2:1. Fig. 40 gives the loss of draft through the breeching per foot of duct for various values of W_a and D_{br}, based on the assumptions noted above.

The ratio factor for a variation in the atmospheric pressure is given by Fig. 19, for a variation in the density of the chimney gases by Fig. 15, for a variation in the coefficient of friction by Fig. 22, and for a variation in the temperature of the chimney gases by Fig. 17.

If the density of the chimney gases is equal to 0.0855 pounds per cu. ft. at 32 deg. Fahr., equation 118 becomes

$$h_{Br} = 0.001\, \frac{W^2_a}{D^5_{br}} \qquad 119$$

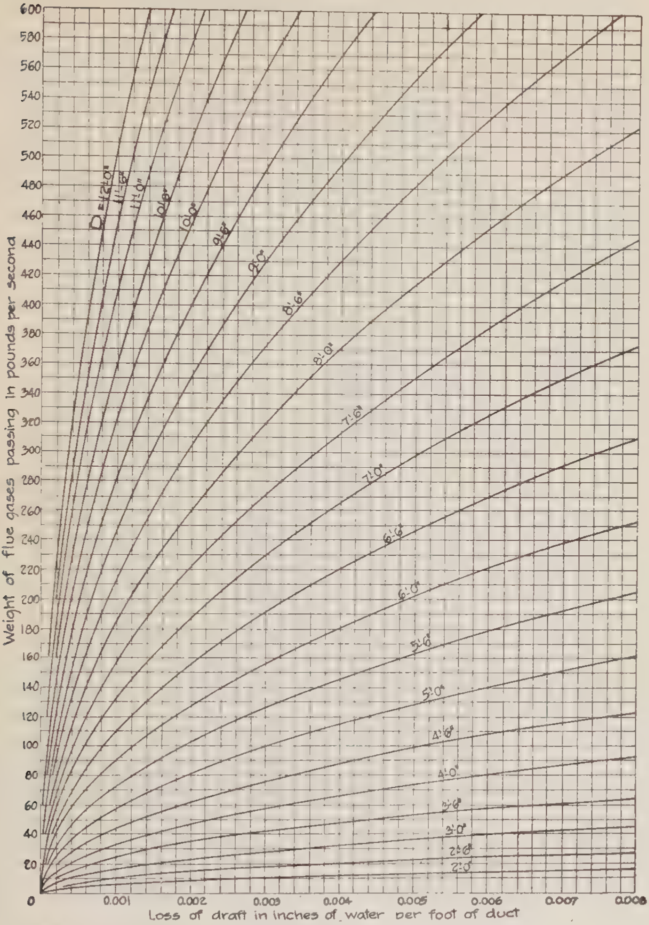

Fig. 40. Loss of Draft through the Breeching

$$h_{Br} = 0.000955 \frac{W^2}{D^5}$$

Based on $t_o = 600$ deg. F., $W_c = 0.08071$, $f = 0.016$, $P_o = P = 14.7$ lbs. per sq. in., and ratio of sides 2:1

In general, assuming a coefficient of friction of 0.016 and a chimney gas temperature of 600 deg. Fahr., equation 110 becomes

$$h_{Br} = 0.001274 \frac{W_a^2 l}{A^2 C_{br}}$$

$$= 0.001274 \frac{W_a^2 l C}{A^3} \qquad 120$$

Whence, the loss of draft through the breeching per foot of duct is equal to

$$h_{Br} = K_{br} W_a^2 \qquad 121$$

in which K_{br} = a constant depending upon the ratio of sides

or $$K_{br} = 0.001274 \frac{C}{A^3} \qquad 122$$

Table 9 gives the value of K_{br} for various ratio of sides.

Size and Shape of Breechings

The size and shape of breechings are of great importance in a steam plant since many draft troubles may be traced directly to improper designs of this connection. As will be seen later on, a breeching with a circular cross-section has the least relative draft loss but a circular breeching is ordinarily more costly than a square or rectangular cross-section, and besides many difficulties are encountered where it connects with the shaft of the chimney, more especially in small chimneys. A circular breeching takes up considerable room and in most plants available space for breechings is at

TABLE 9

PROPERTIES OF VARIOUS SECTIONS OF BREECHINGS

Ratio of height to width.	$\frac{C}{A^3}$	K_{br}	D for A = 1 sq. ft.	h_{Br} per foot of duct.	Relative loss of draft,		
					Circle = 1	1:1 = 1	2:1 = 1
Circular	$\frac{64}{(\pi)^2 D^5_{br}}$	0.008262	1.1284	0.004517 W^2_a	1.00	0.88	0.84
1:1	$\frac{4}{D^5_{br}}$	0.005096	1.0000	0.005096 W^2_a	1.13	1.00	0.94
1½:1	$\frac{40}{27\ D^5_{br}}$	0.001887	0.8160	0.005215 W^2_a	1.15	1.02	0.96
2:1	$\frac{6}{8\ D^5_{br}}$	0.0009555	0.7071	0.005405 W^2_a	1.19	1.06	1.00
2½:1	$\frac{56}{125\ D^5_{br}}$	0.0005707	0.6325	0.005639 W^2_a	1.25	1.11	1.04
3:1	$\frac{8}{27\ D^5_{br}}$	0.0003775	0.5774	0.005882 W^2_a	1.30	1.15	1.08
3½:1	$\frac{72}{343\ D^5_{br}}$	0.0002674	0.5345	0.006129 W^2_a	1.36	1.20	1.13
4:1	$\frac{10}{64\ D^5_{br}}$	0.0001990	0.5000	0.006368 W^2_a	1.41	1.25	1.18
4½:1	$\frac{88}{729\ D^5_{br}}$	0.0001536	0.4714	0.006600 W^2_a	1.46	1.29	1.22
5:1	$\frac{12}{112\ D^5_{br}}$	0.0001223	0.4472	0.006840 W^2_a	1.51	1.34	1.26
5½:1	$\frac{104}{1331\ D^5_{br}}$	0.0000996	0.4264	0.007069 W^2_a	1.56	1.39	1.31
6:1	$\frac{14}{216\ D^5_{br}}$	0.0000826	0.4082	0.007290 W^2_a	1.61	1.43	1.35

a premium. Square breechings also take up considerable horizontal space and likewise are ordinarily difficult to connect with the shaft.

Most breechings are therefore made rectangular in cross-section with the height equal to twice the width, or about this general proportion. This shape requires the least relative horizontal space in the plant and moreover has the added advantage of being able to enter the shaft of most chimneys without inducing complications in regard to the breeching opening.

When an opening is cut into the walls of a masonry chimney, considerable area of a cross-section through the opening is cut away, and unless something is done to strengthen the shaft around this region, the structure is considerably weakened as a consequence. Accordingly, pilasters are built on each side of the breeching-opening to compensate the masonry taken away, the size of the pilasters depending upon the amount of masonry taken away; but, at any rate, the cross-sectional area of the pilasters should equal the cross-sectional area of the opening or the part taken away. It is obvious then that the width of the opening should be as narrow as possible and this accounts for the fact that most breechings are made rectangular in section. Of course, the breeching could be developed from a rectangular section at the breeching entrance of the chimney to any other shape desired between this region and the boiler, but this procedure would incur considerable expense which would not be warranted by the saving in the additional height to the chimney required. The above remarks also apply to steel chimneys in a general way, but the adverse conditions are not so pronounced.

Table 10 gives the size of rectangular sections of breechings entering the shaft of chimneys of various diameters, all based on a ratio of sides of 2:1. The area of the breeching, of course, increases as the number of boilers connected to it increases, the maximum area being over the boiler nearest the chimney, and the same area continuing from thence to the chimney. Since the breeching must convey the same amount of gases as the chimney, it follows that the area of the breeching at its greatest section must be at least as great as the area of the chimney. When breechings of a circular section are used, the areas are made the same. In the case of rectangular sections, however, the area is usually increased over that of the chimney to allow for possible dead air spaces in the corners, etc. The Table gives the size of rectangular openings for three different areas for each diameter, the actual area, the actual area increased by ten per cent, and the actual area increased by twenty per cent. The area of breechings of small chimneys is usually twenty per cent greater than the area of the chimney. This is done, not only to allow for possible dead air spaces in the corners, but also to provide a much wider opening than would otherwise be possible. The area of breechings entering the shaft of large chimneys is usually ten per cent greater than the area of the chimney.

TABLE 10

SIZES OF RECTANGULAR BREECHINGS FOR RATIO OF SIDES OF 2:1

D	A	D_{br}	H_{br}	1.1A	D_{br}	H_{br}	1.2A	D_{br}	H_{br}
3'0"	7.1	1'11"	3' 9"	7.8	2' 0"	3'11"	8.5	2' 1"	4' 2"
3'6"	9.6	2' 2"	4' 5"	10.6	2' 4"	4' 7"	11.5	2' 5"	4' 9"
4'0"	12.6	2' 6"	5' 1"	13.9	2' 8"	5' 2"	15.1	2' 4"	5' 6"
4'6"	15.9	2'10"	5' 8"	17.5	3' 0"	5'10"	19.1	3' 1"	6' 2"
5'0"	19.6	3' 1"	6' 5"	21.6	3' 4"	6' 6"	23.5	3' 5"	6'10"
5'6"	23.8	3' 5"	6'11"	26.2	3' 7"	7' 4"	28.6	3' 9"	7' 7"
6'0"	28.3	3' 9"	7' 7"	31.1	3'11"	7'11"	34.0	4' 2"	8' 2"
6'6"	33.2	4' 1"	8' 2"	36.5	4' 3"	8' 7"	39.8	4' 6"	8'11"
7'0"	38.5	4' 5"	8' 9"	42.4	4' 7"	9' 3"	46.2	4'10"	9' 7"
7'6"	44.2	4' 8"	9' 6"	48.6	4'11"	9'11"	53.1	5' 2"	10' 4"
8'0"	50.3	5' 0"	10' 1"	55.3	5' 3"	10' 7"	60.4	5' 6"	11' 0"
8'6"	56.7	5' 4"	10' 8"	62.4	5' 7"	11' 2"	68.1	5'10"	11' 9"
9'0"	63.6	5' 8"	11' 3"	70.0	5'11"	11'10"	76.3	6' 2"	12' 4"
9'6"	70.9	5'11"	11'11"	78.0	6' 3"	12' 6"	85.1	6' 6"	13' 1"
10'0"	78.5	6' 3"	12' 7"	86.4	6' 7"	13' 1"	94.2	6'10"	13'10"
10'6"	86.6	6' 7"	13' 2"	95.3	6'11"	13' 9"	103.9	7' 2"	14' 6"
11'0"	95.0	6'11"	13' 8"	104.5	7' 3"	14' 5"	114.0	7' 7"	15' 1"
11'6"	103.9	7' 2"	14' 5"	114.3	7' 7"	15' 1"	124.7	7'11"	15' 9"
12'0"	113.1	7' 6"	15' 1"	124.4	7'11"	15' 9"	135.7	8' 3"	16' 6"
12'6"	122.7	7'10"	15' 8"	135.0	8' 3"	16' 5"	147.2	8' 7"	17' 2"
13'0"	132.7	8' 2"	16' 3"	146.0	8' 7"	17' 0"	159.2	8'11"	17'10"
13'6"	143.1	8' 5"	17' 0"	157.4	8'10"	17'10"	171.7	9' 3"	18' 7"
14'0"	153.9	8' 9"	17' 7"	169.3	9' 3"	18' 4"	184.7	9' 7"	19' 4"
14'6"	165.1	9' 1"	18' 2"	181.6	9' 7"	19' 0"	198.1	10' 0"	19'10"
15'0"	176.7	9' 5"	18' 9"	194.4	9'10"	19' 9"	212.0	10' 4"	20' 6"
15'6"	188.7	9' 8"	19' 6"	207.6	10' 2"	20' 5"	226.4	10' 8"	21' 3"
16'0"	201.1	10' 0"	20' 2"	221.2	10' 6"	21' 0"	241.3	11' 0"	22' 0"
16'6"	213.8	10' 4"	20' 8"	235.2	10'10"	21' 8"	256.6	11' 4"	22' 8"
17'0"	227.0	10' 8"	21' 4"	249.7	11' 2"	22' 4"	272.4	11' 8"	23' 3"
17'6"	240.5	11' 0"	21'10"	264.6	11' 6"	23' 0"	288.6	12' 0"	24' 0"
18'0"	254.5	11' 4"	22' 6"	280.0	11'10"	23' 8"	305.4	12' 4"	24' 8"
18'6"	268.8	11' 7"	23' 3"	295.7	12' 2"	24' 4"	322.6	12' 8"	25' 5"
19'0"	283.5	11'10"	23'11"	311.9	12' 6"	25' 0"	340.2	13' 1"	26' 0"
19'6"	298.6	12' 3"	24' 5"	328.5	12'10"	25' 8"	358.3	13' 5"	26' 9"
20'0"	314.2	12' 7"	25' 0"	345.6	13' 2"	26' 4"	377.0	13' 9"	27' 6"

The relative loss of draft through the breechings for various sections is given by Table 9. Fig. 41 shows these results graphically. The equations in the fifth column give the loss of draft through the breeching per foot of duct per sq. ft. area of section, based on a chimney gas temperature of 600 deg. Fahr., a chimney gas density of 0.08071 lbs. per cu. ft. at 32 deg. Fahr., a coefficient of friction of 0.016, and standard atmospheric pressure. For the same cross-sectional area, the relative loss of draft is least through a breeching with a circular section and greatest through a breeching with a

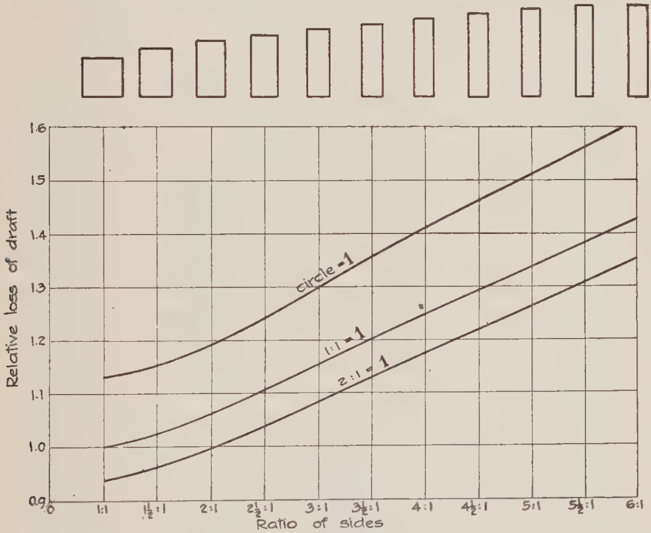

Fig. 41. Relative Loss of Draft for Various Sections of Breeching

Based on $t_c = 600$ deg. F., $W_c = 0.08071$, $f' = 0.016$, and $P_0 = P = 14.7$ lbs. per sq. in.

rectangular section. Based on the same cross-sectional area, the loss of draft through a breeching with a square section is 13 per cent greater and through a breeching with a rectangular section with a ratio of sides of 2:1, 19 per cent greater, than that through a breeching with a circular section. The relative loss of draft increases as the ratio of sides increases, or as the width of the breeching decreases, all other conditions remaining the same.

While the area of the breeching is determined by the amount of gases passing through it, the result should be checked by comparing it with the minimum area of the chimney. The greatest area of the breeching should be at least as large as, but preferably greater than, the minimum area of the chimney itself.

Breechings should always be as short as possible. Overhead breechings are more preferable than underground breechings. The bends in the breeching should have as wide a sweep as possible. The corners of the connection on the inside, especially the one on the side of the direction of flow of the gases, should be rounded in order to decrease the frictional loss and also to prevent eddies.

Application of Equation and Accuracy of Results

In determining the loss of draft through the breeching from equation 117, due allowances should be made for certain factors which affect the loss but which cannot be taken into account in the equation. The equation is based on the theory that the breeching from the farthest boiler to the chimney has the same perimeter and area throughout. Such, however, as a rule, is not the case. Except in the case of small breechings, the area is least over the boiler farthest from the chimney and gradually increases until it is greatest over the boiler nearest the chimney. This area is then maintained from thence to the chimney. The ratio of sides, in the case of a breeching with a rectangular section, is greatest over the boiler nearest the chimney and least over the boiler farthest from the chimney. For convenience, however, in applying the equation, the section assumed is that with the greatest area.

Since the breeching usually connects with several boilers, disturbances in the flow of gases are caused by successive boilers discharging their gases into the duct. Unless the area at every cross-section is amply large, the gases coming from any boiler will tend to retard and obstruct the gases coming from the boilers behind it, thereby tending to produce a back pressure. If the actual area is greater than the required area, this adverse condition will not be so pronounced.

The usual method of determining or estimating the loss of draft through the breeching is to assume a loss of 0.10 inches of water for each 50 feet of straight breeching, regardless of the size or width of the breeching, or the amount of gases passing through it. While this method may be sufficiently accurate for preliminary investigations, an accurate determination of the loss should be made in the final analysis. In large breechings, the loss often is considerably less than the above figure, while in small size breechings, especially those with a narrow width, the loss is considerably greater than the amount noted.

Loss of Draft Due to Turns or Bends

The loss of draft due to turns or bends in the breeching may be computed from the following equation:

$$h_T = 0.10\, W_c\, P_o \frac{V^2_a}{T_c} \qquad 123$$

Based on the weight of gases flowing

$$h_T = 0.0000893 \quad \frac{W^2_a\, T_c}{P_o\, A^2\, W_c} \qquad 124$$

This equation gives the loss for one right-angle turn. In addition to the turns in the breeching, it is necessary to include the turns made when the gases pass from the boiler into the breeching and also from the breeching into the chimney.

Loss of Draft Due to Damper Friction

The loss of draft due to damper friction is arbitrarily regulated by the operator, by opening and closing the damper to regulate the intensity of draft. The minimum loss of draft due to damper friction, when the damper is wide open, is ordinarily included in the loss through the boiler.

When the boilers are operated at high ratings, however, the areas of gas passages through the damper are often inadequate and in this case there will be a restriction and a back pressure. Oftentimes, in badly designed plants, the damper is located at an ill-advised place where it will interfere with a free flow of the gases even when it is wide open, and the loss of draft may amount to as much as 0.20 to 0.30 inches of water.

Loss of Draft through the Economizer

An economizer in a steam plant affects the draft in a two-fold manner, viz:

1. It offers a resistance to the flow of the gases,
2. It lowers the average temperature of the chimney gases and thereby decreases the draft.

Both of the above factors result in an increase in the height of the chimney, and in large plants this may amount to as much as 10 to 15 feet additional.

The loss of draft due to the resistance offered by the tubes of the economizer varies as the length of the tubes and as the square of the velocity of the flue gases. As an average figure for general purposes, the loss may be assumed at 0.25 inches of water for normal rating. The resistance, of course, increases as the rating of the boilers. The loss of draft also varies with the design of the economizer and such data should be obtained from the manufacturer. The loss through the economizer may be computed from the following equation:

$$h_E = \frac{6.606}{(10)^{12}} W^2 N T_c \qquad 125$$

in which W = weight of flue gases in pounds per hour divided by the number of lineal feet of pipe in each section,

and N = number of economizer sections.

The decrease in the temperature of the flue gases after they have passed through the economizer has an extremely important effect on the intensity of the draft. Under average operating conditions, a flue gas with an initial temperature of say 600 deg. Fahr. will be reduced to a temperature of 300 deg. Fahr. to 350 deg. Fahr. after passing through the economizer. Referring to Table 2, it will be seen that for an outside temperature of 60 deg. Fahr., the theoretical draft will be reduced about 38 per cent when the temperature of the chimney gases is lowered from 600 deg. to 300 deg. Fahr.

Loss of Draft Due to Sudden Enlargement of an Opening

In a breeching and also in a chimney, there often come times when it is necessary to suddenly enlarge the section through which the gases have been flowing. This results in a drop of pressure which may be computed from the following equation:

$$h_O = 0.10\ W_c\ P_o\ \frac{V^2_i - V^2_f}{T_c} \qquad 126$$

in which V_i = initial velocity in feet per second,

V_f = final velocity in feet per second.

For a chimney gas temperature of 600 deg. Fahr., the loss due to the sudden enlargement of the opening when the velocity of the gases has been decreased from 30 to 25 ft. per second, for example, will amount to about 0.03 in. of water. It is often necessary to suddenly increase the area or size of the breeching to accommodate a larger boiler. Likewise, in a chimney, there is often a sudden enlargement of the opening at the top of the lining. In either case, the increase in the size of the opening must be sufficient to appreciably lower the velocity of the gases.

Example: Determine the required draft for a chimney from the following data:

Fuel.	Character of fuel, semi-bituminous, Rate of combustion, 25 lbs. of coal per sq. ft. of grate surface per hour.
Boiler.	Type, 3 pass vertical baffle, 12 tubes high, Rate of operation, 250 per cent of its normal rating.
Breeching.	Shape, rectangular with ratio of sides of 2:1, Length of breeching, 50 feet, Width of breeching, 6 feet, Weight of flue gases passing in lbs. per second, 130.
Turns.	One right angle turn in the breeching.

From Fig. 38, the loss through the fuel bed .... = 0.35 inches of water

From Fig. 39, the loss through the boiler .... = 0.70 inches of water

From Fig. 40, the loss through the breeching = 0.0002 × 50 .... = 0.10 inches of water

Loss due to one turn in the breeching .... = 0.05

Total loss, or required draft .... = 1.20 inches of water

In the above example, if the boiler is changed to a 4 pass vertical baffle 14 tubes high with a rating of 225 per cent, the loss of draft through the boiler will equal 0.85 inches of water and the required draft will equal 1.35 inches of water.

If the breeching is changed to a circular section with the same area, the loss through the breeching will be equal to 0.84 × 0.10 = 0.08 inches of water and the required draft will be 1.18 inches of water.

If the rate of combustion is increased to 30 lbs. of coal per sq. ft. of grate surface per hour, the loss through the fuel bed will be equal to 0.47 inches of water and the required draft will be equal to 1.32 inches of water.

Conditions Affecting the Draft Equations

It should be noted in particular that the equations deduced for the theoretical and the available draft of a chimney are purely theoretical equations and give results which are correct only when proper assumptions and correct observations have been made. Most of the constants in the various equations have been fairly well established, and if the required observations have been correctly made, the available draft as given by the equations should accord closely with the actual draft as indicated by a draft-gauge. In actual practice, however, the results are often altered by several factors which are more or less beyond control, or which cannot be expressed in numerical terms. The most important of these are as follows:

1. Non-uniform chimney gas temperature and temperature drop of chimney gases.
2. Strong winds.
3. Heated column of air and gases above top of chimney.
4. Mechanical construction of the top of the chimney.
5. Surrounding hills and buildings.
6. Composition of the chimney gases.
7. Humidity of the atmosphere.
8. Leakages.

Due to the fact that none of the above factors can be expressed in numerical terms, they of course cannot be taken into consideration in the various draft equations. They tend to neutralize one another however, and it is unlikely that the theoretical or the available draft will be seriously affected by any one or several of these factors except in isolated instances.

Effect on the Draft of Non-uniform Chimney Gas Temperature and Temperature Drop of Chimney Gases

It is an established fact that the gases in contact with the inside walls of a chimney are of a lower temperature than those in the center and also that the gases issuing at the top of the chimney are cooler than those entering at the bottom. This non-uniformity of temperature and temperature drop are due to two conditions, viz:

1. Radiation through the walls of the chimney,
2. Cooling action of the walls of the chimney.

There is, in effect, a core of hot gases passing up through a surrounding region of cooler gases whose velocity is decreased by the friction against the walls of the chimney and also by the lowered temperature. This temperature drop varies according to the following:

1. Thickness of the walls of the chimney.
2. Character of the walls of the chimney.
3. Initial temperature of the chimney gases.
4. Velocity of the chimney gases.
5. Height of the chimney.
6. Height of air-space between the lining and the wall of the chimney, and, incidentally, the height of the lining.

In unlined steel chimneys, the radiation is usually considerable but the cooling action of the walls of the shaft, or steel shell, is practically negligible due to the fact that the steel shell, being a good conductor of heat, is always warm. In brick lined steel, brick, and reinforced concrete chimneys there is very little radiation due to the thick walls of the shaft, but the cooling action of the walls is of some consequence. In the latter case, the inside surface of the walls of the chimney may be quite hot while at the same time the outside surface is quite cool. The thinner the walls of the shaft, the greater is the radiation and the less the cooling action, and vice versa.

The lower the velocity of the chimney gases, the longer the chimney gases are in contact with the walls of the shaft and the greater the temperature drop due to radiation and the cooling action. On the contrary, with a high chimney gas velocity, the gases are inside the chimney for such a short interval of time that they do not have time to cool appreciably. The higher the chimney, the longer the gases are in contact with the chimney walls and in confinement, and the greater the temperature drop. The higher the lining, the less is the temperature drop of the chimney gases due to the fact that the lining itself and the air-space between the lining and the wall of the shaft add to the effective thickness of the chimney wall, thereby diminishing radiation and lessening the cooling action of the walls of the shaft. The temperature drop is of more consequence when the temperature of the gases entering the shaft is low than when it is high. Referring to Chapter II, it will be noted that when the chimney gas temperature is lowered from 600 deg. Fahr. to 500 deg. Fahr. for an outside air temperature of 60 deg. Fahr., for example, the theoretical draft will be decreased about 10 per cent, but when the chimney gas temperature is lowered from 1,100 to 1,000 deg. Fahr., the decrease will amount to only about 3.4 per cent.

Due to the great variation in the several factors noted above, it is practically impossible to give even an average figure for the temperature drop of the chimney gases. It has been assumed by some authorities that in steel chimneys, the temperature drop will average about 1 deg. Fahr. per ft. of height of chimney, while in brick lined, brick, and reinforced concrete chimneys, the temperature drop will be from 25 to 50 per cent of this figure.

When calculating the draft of a chimney, the average chimney gas temperature is used in determining the difference in pressure. The average chimney gas temperature should be observed by a good pyrometer and should be ascertained in no other manner. As stated before, the theoretical draft of a chimney is dependent upon the difference in temperature between the outside air and the chimney gases and since the temperature of the outside air can be observed accurately, the accuracy of the preliminary calculations is dependent upon the accuracy with which the temperature of the chimney gases is observed.

Effect of Strong Winds on the Draft

Strong winds sometimes prevent an easy egress of the gases by blowing them away from a vertical course and against the inside of the shaft at the top, thereby flattening the escaping column of gases and acting partially as a damper. Often, downward eddies are formed on the inside. This results in a back pressure and will tend to diminish the effective pressure, especially if the velocity of the wind is greater than the velocity of the escaping column of gases. Chimneys with large diameters at the top are more easily affected than those with small or medium-size diameters.

On the other hand, winds may in some instances actually increase the intensity of the draft by producing an upward effect and thereby increasing the velocity of the escaping gases. Strong winds, when blowing from the right quarter, often materially increase the pressure at the furnace entrance and thereby increase the draft. A wind from the opposite quarter may have a reverse effect.

Effect on the Draft of the Heated Column of Air and Chimney Gases above the Top of the Chimney

In a quiet and undisturbed atmosphere with no wind blowing, the issuing gases will often be seen to take a distinctly vertical course for several feet above the top of the chimney before dissipating themselves. This is especially noticeable on cool and frosty mornings in the autumn and winter and also during the summer evenings when the temperature of the atmosphere is slowing falling and the air is perfectly quiet. This phenomenon often results in a very noticeable increase in the intensity of the draft and is due to the fact that the surrounding atmosphere, being denser than the chimney gases, acts in effect as an increase in the height of the chimney.

Effect on the Draft of the Mechanical Construction of the Top of the Chimney

The mechanical construction of the top of the chimney may have an appreciable effect on the intensity of the draft, especially when a strong wind blows. In designing the head of a chimney, the aim should be to force the gases upwards by directing them in an upward course as shown in Fig. 42, rather than to allow the wind to blow directly across the top or even to produce downward eddies as shown in Fig. 43. The head of the chimney should have a projection or corbelling a foot or so below the top in order to give the wind an upward direction. The top should be flat and not rounded, as shown in Fig. 44, otherwise the wind may start eddies at the top with a downward course and produce a back pressure.

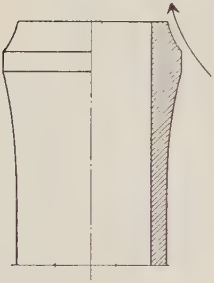

Fig. 42

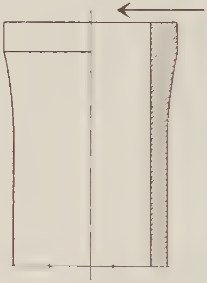

Fig. 43

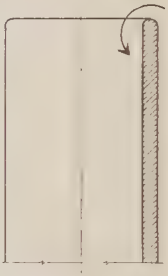

Fig. 44

Effect on the Draft of Surrounding Hills and Buildings

The proximity to the chimney of tall buildings or hills may have an effect on the draft of an appreciable amount. Tall buildings often produce complex wind currents with both upward and downward eddies, the former aiding and the latter hindering the draft. In large cities, where building space is at a premium and it is impossible to build an isolated chimney for the heating plant of a large building, the chimney is either built in the corner of the building on the inside or is anchored to the building itself on the outside. This often results in a much higher chimney than is actually necessary with a consequent excess of draft. If the chimney is located in a "pocket" or is surrounded by hills or bluffs, the draft is less liable to be affected by winds than if it stands out in an open prairie or on top of a high hill.

Effect on the Draft of the Composition of the Chimney Gases

As discussed in a previous section, the intensity of the draft decreases as the density of the chimney gases increases, all other factors or conditions remaining constant. Ordinarily the density of the chimney gases depends upon their composition as well as upon their temperature. The composition of the chimney gases may have an indirect effect upon the draft, especially when they are heavily laden with foreign particles or matter such as soot, ashes, carbon particles, etc. These foreign particles doubtless decrease the draft by increasing the friction between the gases and the wall of the shaft. It is often necessary to place soot collectors inside the chimney and these provide additional resistance to the flow of the gases.

Effect of Humidity on the Draft

The humidity of the atmosphere always affects the draft to an appreciable extent, but in a manner which is difficult to express in numerical terms. When the air is heavily laden with moisture, the draft is sluggish because the air, being much heavier than the escaping column of chimney gases, bears down heavily upon the latter and acts in effect as a damper. It is difficult for the escaping gases to pierce the moisture laden air, and additional frictional resistance is thus created.

Effect of Leakages on the Draft

The effect of leakages on the draft is uncertain. Infiltrating air in the chimney certainly tends to lower the temperature of the chimney gases and thereby decreases the draft. The effect is perhaps more pronounced when the velocity of the chimney gases is high as the air will then be sucked in at a greater rate than if the velocity is low. Most of the leakages come from around the breeching opening and are due to improper fitting or packing. Cracks and vents in the shaft of the chimney are due to carelessness in construction and are uncalled for. In case cracks appear, they should be repaired immediately.

CHAPTER VI

THE HEIGHT OF THE CHIMNEY

The ultimate purpose or object of a detailed analysis of the draft losses throughout a steam boiler plant installation is to provide data for determining the *required* height of the chimney. The required height of the chimney is always measured from the level of the grates regardless of the location of the breeching opening even though the latter, for instance, is located some distance up the shaft. Oftentimes the grate level is much higher than the ground level but the shaft of the chimney must, of necessity, extend at least to the latter datum plane. The total length of the shaft, that is to say, the height above the top of the foundation is called the *actual* height. All vertical passes in the boiler and the breeching are considered, in effect, as a part of the required height of the chimney, the only difference being that the gases are flowing in the boiler and the breeching instead of in the chimney. The greater the length of the vertical passes, the greater is the chimney action.

From equation 22:

$$H = \frac{D_t}{K_D} \qquad 127$$

For a chimney gas density of 0.08071 lbs. per cu. ft. at 32 deg. Fahr. and standard atmospheric pressure:

$$K_D = 7.63 \left(\frac{1}{T_o} - \frac{1}{T_c}\right)$$

Hence $$H = \frac{D_t}{7.63\left(\frac{1}{T_o} - \frac{1}{T_c}\right)} \qquad 128$$

Fig. 45 gives the theoretical height of a chimney for various values of theoretical draft, D_t, and chimney gas temperature, t_c, based on an outside air temperature of 60 deg. Fahr. The theoretical height of a chimney is equal to the required height when the theoretical draft is equal to the sum of all the losses of draft throughout the installation.

Example: Determine the theoretical height of a chimney which will produce a theoretical draft of 1.50 inches of water with an outside air temperature of 60 deg. Fahr. and a chimney gas temperature of 600 deg. Fahr.

Substituting in equation 128 and reducing:

$$H = \frac{1.5}{7.63\left(\frac{1}{519.6} - \frac{1}{1059.6}\right)} = \frac{1.5}{0.00748} = 200 \text{ ft.}$$

Or, from Fig. 45, the theoretical height, H, for a theoretical draft, D_t of 1.50 inches of water and a chimney gas temperature, t_c, of 600 deg. Fahr. is equal to 200 ft.

Now from equation 127:

$$D_t = K_D H$$

and from equation 109:

$$D_t = h_F + h_B + h_{Br} + h_T + h_D + h_v + h_f \qquad 129$$

to which should be added

$$h_O + h_E$$

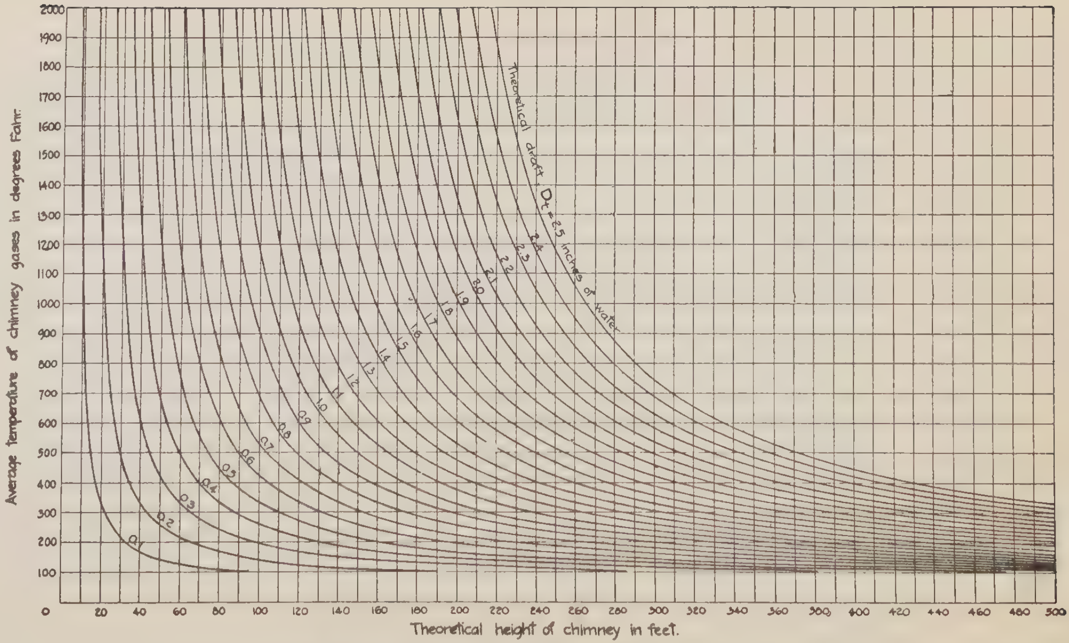

Fig. 45. **Theoretical Height of Chimney for various Chimney Gas Temperatures Based on $t_0 = 60$ deg. Fahr., $W_c = W_0 = 0.08071$, and $P_0 = P = 14.7$ lbs. per sq.in.**

in case it is necessary to consider these two factors.

Whence

$$K_DH = h_F + h_B + h_{Br} + h_T + h_D + h_O + h_E + h_v + h_f \qquad 130$$

$$\text{Then } H = \frac{h_F + h_B + h_{Br} + h_T + h_D + h_O + h_E + h_v + h_f}{K_D} \qquad 131$$

$$= \frac{D_t}{K_D}$$

The required height of a chimney above the grate level, then, is equal to the sum of the several losses of draft throughout the whole installation, or along the path of the gases, divided by the theoretical draft per foot of chimney, both expressed in inches of water and both based on the same operating conditions. The required height of the chimney is equal to the theoretical height when the sum of all of the various losses of draft is equal to D_t.

In equation 131, the terms h_D, h_O and h_E may be disregarded, as a general rule, since they are seldom encountered in an average plant. In case there is a loss of draft through the damper or through an economizer when the latter is not a part of the boiler, or due to a sudden enlargement of an opening, the proper value, or values, should be included. It is only in rare instances that such cases will occur.

Example: Determine the required height of a chimney for the following conditions:

60 deg. Fahr., temperature of the outside air,
600 deg. Fahr., temperature of the chimney gases,
0.40 in. of water, loss of draft through the fuel bed,
0.65 in. of water, loss of draft through the boiler,
0.15 in. of water, loss of draft through the breeching,
0.10 in. of water, loss of draft due to turns or bends,
0.10 in. of water, loss of draft due to velocity,
0.10 in. of water, loss of draft due to friction.

Substituting in equation 131 and reducing:

$$H = \frac{0.40 + 0.65 + 0.15 + 0.10 + 0.10 + 0.10}{7.63\left(\frac{1}{519.6} - \frac{1}{1059.6}\right)}$$

$$= \frac{1.50}{0.00748} = 200 \text{ ft.}$$

Or, from equation 129:

$$D_t = 0.40 + 0.65 + 0.15 + 0.10 + 0.10 + 0.10$$

$$= 1.50 \text{ inches of water}$$

and from Fig. 45 the height of chimney required for a chimney gas temperature of 600 degrees Fahr. and a theoretical draft of 1.50 inches of water is equal to 200 ft.

Of the nine terms composing the numerator of the right hand member of equation 131, only two terms, exclusive of the three noted heretofore (h_D, h_O, and h_E) which are seldom encountered, cannot be expressed by an equation, viz: h_F and h_B. It is necessary to get values for these two factors from curves which have been plotted from experiments. Figs. 38 and 39 are two such typical curves.

Equations 132, 133, 134, and 135 give the required height of a chimney with all of the observable conditions taken into consideration. Equations

132 and 134 are based on the velocity of the gases and equations 133 and 135 on the weight of gases flowing. Equations 134 and 135 are in a reduced form and are based on $f = 0.016$, $W_c = 0.0855$, $P_0 = 14.7$, a breeching with a height equal to twice the width and a circular section of chimney.

Now the principal factors which affect the loss of draft through the fuel bed are:

1. Character of fuel burned,
2. Amount of fuel burned per square foot of grate surface per hour, or the rate of combustion.

The loss of draft through the boiler is affected mainly by:

1. Type and size of boiler,
2. Rate of operation.

From the equations and data given herewith, the required height of a chimney is affected by the following:

1. Character of fuel burned,
2. Rate of combustion,
3. Type and size of boiler,
4. Rate of operation,
5. Quantity of gases flowing,
6. Temperature of flue and chimney gases,
7. Length of breeching,
8. Size of breeching,
9. Coefficient of friction,
10. Density of chimney gases,
11. Atmospheric pressure,
12. Length of chimney duct,
13. Diameter of chimney,
14. Temperature of outside air.

General equation for required height of chimney based on velocity of gases flowing:

$$H = \frac{h_F + h_B + 0.10\, f\, W_c\, P_o \frac{V^2_a}{T_c} \frac{1}{C_{br}} + 0.10\, W_c\, P_o\, X_T \frac{V^2_a}{T_c} + 0.10\, W_c\, P_o \frac{V^2_a}{T_c} + 0.10\, f\, W_c\, P_o \frac{V^2_a}{T_c} \frac{L}{C_d}}{6.43\, P_o \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right)} \qquad 132$$

General equation for required height of chimney based on weight of chimney gases flowing:

$$H = \frac{h_F + h_B + 0.0000893\, f \frac{W^2_a\, T_c\, 1\, C}{P_o\, A^3\, W_c} + 0.0000893\, X_T \frac{W^2_a\, T_c}{P_o\, A^2\, W_c} + 0.0000893 \frac{W^2_a\, T_c}{P_o\, A^2\, W_c} + 0.0000893\, f \frac{W^2_a\, T_c\, L\, C}{P_o\, A^3\, W_c}}{6.43\, P_o \left(\frac{W_o}{T_o} - \frac{T_c}{W_c}\right)} \qquad 133$$

For $f = 0.016$, $P_o = 14.7$, $W_o = 0.08071$, $W_c = 0.0855$, circular section of chimney and breeching with ratio of sides of 2:1:

Equation 132 reduces to:

$$H = \frac{h_F + h_B + 0.006 \frac{V^2_a}{T_c} \frac{1}{D} + 0.1255\, X_T \frac{V^2_a}{T_c} + 0.1255 \frac{V^2_a}{T_c} + 0.008 \frac{V^2_a}{T_c} \frac{L}{D}}{7.63 \left(\frac{1}{T_o} - \frac{1.06}{T_c}\right)} \qquad 134$$

Equation 133 reduces to:

$$H = \frac{h_F + h_B + 0.000000852 \frac{W^2_a\, T_c\, 1}{D^5_{br}} + 0.0000178\, X_T \frac{W^2_a\, T_c}{D^4_{br}}\ 0.000115 \frac{W^2_a\, T_c}{D^4} + 0.00000737 \frac{W^2_a\, T_c\, L}{D^5}}{7.63 \left(\frac{1}{T_o} - \frac{1.06}{T_c}\right)} \qquad 135$$

The value of each of the above factors can be computed from data or may be observed by instruments, with the exception of the diameter of the chimney and the length of the chimney duct. Hence, in computing the required height of a chimney, it is necessary either to assume a value for the diameter and a value for the length of the chimney duct, or to assume arbitrary values for the loss due to velocity and the loss due to friction. In any problem involving the diameter of the chimney, the approximate diameter may be estimated closely by assuming an average velocity of the chimney gases and dividing this value into the quantity of gases flowing. For the purpose of arriving at a trial height of chimney, fairly close results will be obtained by assuming a loss of draft of 0.10 inches of water for the loss due to friction and the same amount for the loss due to velocity.

A set of average operating conditions for a coal-fired plant will now be assumed, and the required height of chimney will then be computed, using equations 132, 133, 134, and 135 as a basis for determining the losses of draft.

The following set of average operating conditions will be assumed:

1. W. Va. semi-bituminous coal, character of fuel,
2. 25 pounds of coal per square foot of grate surface per hour, rate of combustion,
3. Vertical baffled 4-pass boilers 14 tubes high with total grate surface of 660 square feet,
4. 220 per cent, boiler rating,

5. 90 pounds per second, quantity of gases flowing,
6. 600 degrees Fahr., temperature of flue and chimney gases,
7. 60 feet, length of breeching,
8. 6′6″ wide × 13′0″ high, size of breeching,
9. 0.016, coefficient of friction,
10. 0.0855, density of chimney gases,
11. 14.5 pounds per square inch, atmospheric pressure,
12. Length of chimney duct, 18 feet less than the required height of the chimney,
13. Diameter of chimney to be approximated,
14. 60 degrees Fahr., temperature of the outside air.

Loss of Draft through the Fuel Bed (Items 1 and 2)

The loss of draft through the fuel bed, h_F, for W. Va. semi-bituminous coal when burned at a rate of 25 pounds per square foot of grate surface per hour, as given by Fig. 38, is equal to 0.35 in. of water.

Loss of Draft through the Boiler (Items 3 and 4)

The loss of draft through the boiler, h_B, for a 4-pass vertically baffled boiler 14 tubes high when operated at 220 per cent rating, as given by Fig. 39, is equal to 0.80 inches of water.

Loss of Draft through the Breeching (Items 5, 6, 7, 8, 9, 10, 11)

From equations 117 and 135:

$$H_{Br} = 0.0000893 \times 0.016 \times \frac{(90)^2 \times 1059.6 \times 60 \times 39}{14.5 \times (84.5)^3 \times 0.0855}$$
$$= 0.04 \text{ in. of water}$$

It should be noted that when the various losses are based on the quantity of gases flowing, the loss varies inversely as the atmospheric pressure.

Loss of Draft Due to Turns or Bends in the Breeching (Items 5, 6, 8, 10 and 11)

Assume one right angle bend. From equations 124 and 133:

$$h_T = 0.0000893 \times \frac{(90)^2 \times 1059.6}{14.5 \times (84.5)^3 \times 0.0855}$$

$$= 0.09 \text{ in. of water}$$

Loss of Draft Due to Velocity of the Chimney Gases (Items 5, 6, 10, 11, 12 and 13)

The diameter of the chimney at this stage of the analysis is unknown, therefore it is necessary to select a trial value. This is arrived at as follows: 90 lbs. of chimney gases per second at a chimney gas temperature of 600 degrees Fahr. is equal to 2,270 cu. ft. per second. Assuming an average chimney gas velocity of 28 ft. per second, the area of the chimney would be equal to

$$\frac{2270}{28} = 80 \text{ sq. ft.}$$

from whence the diameter is equal to 10 feet, approximately. Then from equations 42 and 133:

$$h_v = 0.0000893 \times \frac{(90)^2 \times 1059.6}{14.5 \times (80)^2 \times 0.0855}$$

$$= 0.10 \text{ inches of water}$$

Loss of Draft Due to Friction (Items 5, 6, 9, 10, 11, 12 and 13)

The length of the friction duct of the chimney is unknown and it is therefore necessary to select a trial value. This is arrived at as follows:

From the foregoing data:

Loss of draft through the fuel bed	= 0.35 in. of water
Loss of draft through the boiler	= 0.80 in. of water
Loss of draft through the breeching	= 0.04 in. of water
Loss of draft due to turns	= 0.09 in. of water
Loss of draft due to velocity	= 0.10 in. of water
Assume loss of draft due to friction	= 0.10 in. of water
Total trial loss of draft	= 1.48 in. of water

The theoretical draft per foot of chimney (items 6 and 14) as given by equation 23 is equal to

$$K_D = 7.63 \left(\frac{1}{519.6} - \frac{1}{1059.6}\right)$$

$$= 0.00748 \text{ inches of water}$$

From Fig. 10, the correction factor for a chimney gas density of 0.0855 pounds per cubic foot at 32 degrees Fahr. is equal to 0.00042 inches of water. Whence, the theoretical draft corrected for chimney gas density equals

$$K_D = 0.00748 - 0.00042 = 0.00706 \text{ in. of water}$$

Corrected for atmospheric pressure,

$$K_D = 0.00706 \times 0.987 = 0.00697 \text{ in. of water}$$

Then from equation 127:

$$\text{Trial } H = \frac{1.48}{0.00697} = 212 \text{ feet}$$

and $\text{Trial } L = 212 - 18 = 194 \text{ feet}$

Whence, from equations 66 and 133:

$$h_f = 0.0000893 \times 0.016 \times \frac{(90)^2 \times 1059.6 \times 194 \times 31.4}{14.5 \times (80)^3 \times 0.0855}$$

$$= 0.12 \text{ inches of water}$$

The trial assumption for the loss of draft due to friction proved to be too small and a second assumption must be made.

Assume loss of draft due to friction = 0.12 inches of water.

Then the total loss of draft = 1.50 inches of water.

Whence, from equation 127, as before:

$$\text{Trial H} = \frac{1.50}{0.00697} = 215 \text{ feet}$$

and $\text{Trial L} = 215 - 18 = 197$ feet

Then, as before,

$$h_f = 0.0000893 \times 0.016 \times \frac{(90)^2 \times 1059.6 \times 197 \times 31.4}{14.5 \times (80)^3 \times 0.0855}$$

$$= 0.12 \text{ inches of water}$$

Since the assumed loss of draft due to friction is equal to the computed loss, the trial L is equal to the actual L, and no further correction is necessary.

Finally, the total loss of draft throughout the installation from the data given and as developed by the above calculations is equal to:

Loss of draft through the fuel bed	= 0.35 in. of water
Loss of draft through the boiler	= 0.80 in. of water
Loss of draft through the breeching	= 0.04 in. of water
Loss of draft due to turns	= 0.09 in. of water
Loss of draft due to velocity	= 0.10 in. of water
Loss of draft due to friction	= 0.12 in. of water
Total loss of draft	= 1.50 in. of water

The theoretical draft per foot of chimney, as given before, equals

$$0.00697 \text{ inches of water}$$

Whence, the required height of chimney as given by equation 131 equals:

$$\frac{1.50}{0.00697} = 215 \text{ feet}$$

Quantity of Gases Flowing

It was assumed that the quantity of gases flowing is equal to 90 lbs. per second. This value was arrived at as follows: The total grate surface of the boilers is equal to 660 sq. ft. Since the rate of combustion was assumed at 25 lbs. of coal per sq. ft. of grate surface per hour, the total amount of coal burned equals

$$660 \times 25 = 16{,}500 \text{ lbs. per hour}$$

An analysis of the coal is necessary to determine the theoretical amount of air required per pound of coal. Let it be assumed that an analysis of the coal gave the following results:

82 per cent carbon
5 per cent hydrogen
4 per cent oxygen
1 per cent sulphur
3 per cent nitrogen
5 per cent ash (by difference)

Then the theoretical weight of air required per pound of coal equals:

$$\begin{aligned} W_{ta} &= 11.56 \times 0.82 + 34.56 \left(0.05 - \frac{0.04}{8}\right) + 4.32 \times 0.01 \\ &= 9.48 + 1.56 + 0.04 \\ &= 11.08 \end{aligned}$$

Assuming that 70 per cent excess air is required, the total weight of the products of combustion per pound of coal equals

$$W_{tp} = 11.08 \times 1.70 + 0.82 + 0.04 + 0.01$$
$$= 20 \text{ lbs. of gas (approximately)}$$

Whence, the total weight of gases formed equals

$$16{,}250 \times 20 = 325{,}000 \text{ lbs. per hour}$$

or $$\frac{325{,}000}{3600} = 90 \text{ lbs. per second}$$

Size of Breeching

The size of the breeching was determined as follows: 90 lbs. of gases at a flue gas temperature of 600 deg. Fahr. equals 2,270 cu. ft. per second. Assuming an average flue gas velocity of 28 ft. per second, the minimum area of the flue or breeching would be equal to

$$\frac{2270}{28} = 80 \text{ square feet}$$

Allowing an excess of 5 per cent, the required area then equals 84 sq. ft. Assuming a rectangular breeching with a height equal to twice the width or a ratio of sides of 2:1,

$$2\ D_{br} \times D_{br} = 2\ D^2_{br} = 84$$
$$D^2_{br} = 42$$

Whence $$D_{br} = 6.5$$

and $$H_{br} = 2\ D_{br} = 13.00$$

General

The foregoing presents a fairly accurate and complete method of determining the required height of a chimney. It should be borne in mind that the example which has been worked out in detail represents an assumed set of operating conditions. Of course these operating conditions may vary from day to day, or even from minute to minute, and as a consequence, the required height of the chimney will also vary. Unfortunately, it is not possible or even practicable to build a telescoping chimney which could be adjusted in height, and even in diameter, to meet the variation in various operating conditions as they deviate from those made in the assumption. As long as the total loss of draft remains at or around 1.50 inches of water, as noted in the example, a chimney 215 feet in height will create sufficient draft to overcome all of the resistances, provided the chimney gas temperature and the temperature of the outside air do not change appreciably. The maximum loss of draft through the fuel bed and also through the boiler has been included in the total loss and as long as the rate of combustion of the coal remains at or below 25 lbs. per sq. ft. of grate surface per hour, and the rate of operation of the boilers remains at or below 220 per cent of normal rating, there will never be any increase in the loss of draft through these two parts.

The losses through the breeching, due to turns, due to velocity and due to friction are all based on a chimney and flue gas temperature of 600 degrees Fahr. and will vary with the temperature of these gases. Likewise, the theoretical draft per foot of chimney varies as the temperature of the chimney gases. It will be shown later on that the required height of a chimney decreases as the temperature of the flue and chimney gases increase, all other conditions remaining constant. On the other hand, the required height of a chimney increases as the temperature of the outside air increases, all other conditions remaining constant. All of the factors entering into the equation for the required height of a chimney, affect the height in one way or another when they vary from the original assumption. In computing the required height of a new chimney, these variations affect the ultimate height at which the chimney will be built, while in the case of a working chimney the variations in the loss of draft affect the performance of the chimney.

The usual or approximate method of determining the required height of a chimney is to ascertain the loss of draft through the fuel bed and the loss through the boiler from curves, approximate the loss of draft through the breeching and the loss due to turns from arbitrarily set units, increase the sum of these four losses by 25 per cent, and then divide the sum of these four losses and the 25 per cent increase by the theoretical draft per foot of chimney. The increase of 25 per cent is due to the assumption that the available draft is equal to 80 per cent of the theoretical draft. The loss through the breeching is usually taken or assumed at about 0.10 inches of water per 100 lineal feet of breeching and the loss due to turns as 0.05 inches of water for each right angle turn or bend. Applying the above method or approximation to the example given heretofore:

Loss of draft through the fuel bed (from curves) = 0.35 in. of water
Loss of draft through the boiler (from curves) = 0.80 in. of water
Loss of draft through the breeching $(0.10 \times 60/100)$ = 0.06 in. of water
Loss of draft due to turns = 0.05 in. of water

1.26 in. of water
25 per cent increase = 0.32 in. of water

Total loss of draft = 1.58 in. of water

The value "K," or the theoretical draft per foot of chimney is usually given as 0.0075 for a chimney gas temperature of 600 deg. Fahr. Whence, the required height equals

$$H = \frac{1.58}{0.0075} = 210 \text{ feet}$$

The required height of the chimney by this method is 5 feet less than that determined by the more accurate method.

Even though the results by the two methods are fairly close, yet the approximate method of determining the required height of a chimney is inaccurate and is liable to produce some extremely inaccurate results, especially in the case of the smaller size chimneys. The actual available draft, in this case, is equal to

$$1.58 - 0.32 = 1.26 \text{ inches of water}$$

which is equal to about 80 per cent of the theoretical draft, assuming that the theoretical draft is equal to the total loss of draft. The actual theoretical draft per foot of chimney is equal to only 0.00697 inches of water, a difference of 0.00053 inches of water. This difference is due to the fact that the value of 0.0075 has not been corrected for chimney gas density and atmospheric pressure. If the approximated loss of draft was divided by the correct theoretical draft per foot of chimney, the required height would equal

$$\frac{1.58}{0.00697} = 226 \text{ feet}$$

The theoretical draft per foot of chimney should always be corrected for the proper chimney gas density. The usual density assumed is 0.0855 lbs. per cu. ft. at 32 deg. Fahr. which perhaps comes very near the average density. The density of the chimney gases is certainly greater than that of the outside air.

One of the greatest mistakes in determining the required height of a chimney is that of assuming that the available draft is equal to 80 per cent of the theoretical draft. This ratio, on the average, is not even approximately true. In small chimneys, with small diameters, the available draft is usually between 60 and 70 per cent of the theoretical draft, while in large chimneys, with large diameters, it is equal to 85 to 90 per cent of the theoretical draft. In large chimneys, the loss of draft due to friction is almost negligible, and this increases the ratio percentage.

Neglect of losses of draft should be carefully guarded against. Oftentimes in large installations, the economizer is not included as a part of the boiler but is placed in the breeching, or at any rate in such a location that the flue gases must pass through it. In this case, a value for the loss through the economizer must be included in the total loss of draft. Likewise, when the inside diameter of the shaft at the level where the breeching enters is large, there will be a sudden enlargement of an opening and another value must be added to take care of this loss. There may be several bends in the breeching and the loss for one bend must be multiplied by the number of bends.

The cardinal sin in calculating the size of chimneys is in the attempt to arrive at definite results with insufficient information. The required height of a chimney cannot be determined accurately with insufficient data any more than a building or a bridge can be designed with insufficient preliminary information. When an attempt is made to determine the required height of a chimney, at least the fourteen items as noted heretofore should be known. Certainly the amount of gases flowing should be one of the first items known, yet how many designers get this information at first. Arriving at the height of a chimney without knowing the amount of gases flowing is worse than trying to arrive at the size of a pipe without knowing how much water is to be taken care of.

The height to which a contemplated chimney is to be built should be the ultimate height which will ever be required. When a chimney is built too short, the situation is practically hopeless, as far as creating more natural draft is concerned.

CHAPTER VII

ELEMENTS OF COMBUSTION

Combustion is the chemical union, or combination, of the oxygen of the air with one, or more, of the combustibles of a fuel, such as carbon, hydrogen, or other elements. This chemical union is very rapid and is accompanied by a liberation of heat and light. Combustion is perfect or imperfect according as: the combustible unites with the necessary amount of oxygen and the process is complete, or, there is an excess of oxygen and the process is incomplete. The perfect combustion of a fuel should result in carbon dioxide, nitrogen, and vapor.

Air

The atmosphere, or air, is a mechanical mixture of several constant and variable ingredients as follows:

The constant ingredients are:

1. Nitrogen,
2. Oxygen,
3. Argon,
4. Helium,
5. Krypton,
6. Hydrogen.

The variable ingredients are:

1. Water vapor,
2. Carbon dioxide,
3. Ozone,
4. Hydrogen peroxide,
5. Ammonium nitride,
6. Dust and bacteria.

Pure air is a mixture of the constant ingredients of the air. In general, pure dry air contains 79.09 per cent nitrogen and 20.91 per cent oxygen by volume, or 76.85 per cent nitrogen and 23.15 per cent oxygen by weight. The other elements occur in very small quantities and are included in the oxygen percentages.

Oxygen is the supporter of combustion while nitrogen is inert. Nitrogen acts as a diluent and greatly reduces the activity of the oxygen as well as lowers the temperature of combustion. Oxygen also exists in coal as a compound with hydrogen in the form of water. The combining weight of oxygen is 16 and that of nitrogen 14.

Fuels

Fuels may be broadly classified as follows:

- Solid fuels.
  - Natural
    - Coal
      - Anthracite
      - Semi-bituminous
      - Bituminous

        - Wood
            - Hard
            - Soft
        - Peat
        - Lignite
        - Straw
    - Prepared
        - Charcoal
        - Coke
        - Peat
        - Briquetted fuels
- Liquid fuels.
    - Natural
        - Crude oils
    - Prepared
        - Distilled oils
- Gaseous fuels.
    - Natural
        - Natural gas
    - Prepared
        - Coal gas
        - Water gas
        - Producer gas
        - Oil gas

The principal ingredients of fuels are:

1. Carbon
2. Hydrogen
3. Oxygen
4. Nitrogen
5. Sulphur

During the process of combustion, a fuel is segregated into carbon and volatile gases. The volatile gases which are distilled from the fuel before being burned are called hydrocarbons and are represented by marsh gas, olefant gas, tar, pitch and naphtha. After the volatile gases have been driven off, fixed carbon remains. Ash is the incombustible material which remains after the fuel has been burned. The three ingredients which are determined in the commercial analysis of a fuel are:

1. Fixed carbon,
2. Volatile matter,
3. Ash.

In determining the heat value of a fuel, the following are considered:

1. Oxygen,
2. Hydrogen,
3. Sulphur.
4. Carbon.

The heat value of a fuel is expressed in terms of b.t.u.'s per pound.

Carbon

Carbon is found in a pure state as graphite and diamond. It exists in fuels in two forms, viz:

1. Fixed carbon,
2. Hydrocarbon combinations.

Fixed carbon is the pure carbon of the fuel. It remains unchanged when the fuel is heated and the volatile matter and moisture are driven off. The result of a union of hydrogen and carbon is called a hydrocarbon. This is the volatile state of carbon.

Carbon combines with oxygen in two ways. If sufficient air is supplied to every particle of carbon, complete combustion results and carbon dioxide is formed:

$$C + 20 = CO_2 \qquad 136$$

If insufficient air is supplied to the particles of carbon, incomplete combustion takes place and carbon monoxide will be formed:

$$C + O = CO \qquad 137$$

Carbon dioxide is an inert gas while carbon monoxide is combustible and will unite with oxygen to form carbon dioxide:

$$CO + O = CO_2 \qquad 138$$

Hydrogen

Hydrogen exists in fuels as a compound of both carbon and oxygen in the form of hydrocarbons and water. Hydrocarbons form the principal part of the volatile matter in fuels, that is to say, they are the part of the fuels which are driven off in a gaseous state. Hydrogen in combination forms the moisture content of the fuel. Hydrogen is very combustible and, unlike carbon, always burns completely.

$$2H + O = H_2O \qquad 139$$

The combining weight of hydrogen is 1.

Sulphur

Sulphur is found in most fuels in the form of iron sulphide. When present in small quantities, its effect is negligible. When fuels contain from four to five per cent of sulphur, however, difficulty is experienced in burning them, even though sulphur itself is combustible. Sulphur lowers the fusion temperature of ash and causes the formation of clinkers. Sulphur also unites with hydrogen and oxygen forming acids which quickly attack and corrode steel. The combining weight of sulphur is 32.

In addition to the elements mentioned, solid fuels contain water, ash, and other foreign substances such as oxygen and nitrogen.

TABLE 11

Element	Combining Weight	Formula	Pounds of Oxygen required per Lb. of Combustible	Pounds of Air required per Lb. of Combustible	Calorific Value in B.t.u. per Lb. of Combustible
Carbon, C	12	$C + O = CO$	1⅓	5.76	4,450
		$C + 2O = CO_2$	2⅓	11.52	14,600
		$CO + O = CO_2$	4/7	2.47	4,350
Hydrogen, H	1	$2H + O = H_2O$	8	34.56	62,000
Nitrogen, N	14				
Oxygen, O	16				
Sulphur, S	32	$S + 2O = SO_2$			
		$S + 3O = SO_3$			

Air supplied for combustion

When coal is burned in a boiler, the volatile matter of the fuel unites with the oxygen in the air and a definite amount of heat is liberated which is made available for generating steam. The temperature of the resulting gases depends, among other factors, upon the quantity of gas to be heated and, all other things being equal, the temperature will vary inversely as the amount of excess air. That is to say, the greater the excess air, the lower the temperature. The weight of air supplied for combustion determines to a great extent the efficiency of the furnace and is a very important factor in determining the available draft of a chimney. From the weight of the air supplied and the amount of coal burned can be determined the amount of resulting gases and consequently the amount of gases passing up the chimney.

The weight of air to be supplied for proper combustion may be determined by two methods, viz:

1. By analysis of the coal, or fuel
2. By analysis of the flue or furnace gases.

Air is composed of 21 per cent oxygen and 79 per cent nitrogen, by volume, or 23.15 per cent oxygen and 76.85 per cent nitrogen, by weight. Hence, when one pound of oxygen is burned, there must be supplied

$$\frac{76.85}{23.15} = 3.32 \text{ lbs. of nitrogen}$$

and for every pound of oxygen required, there must be supplied 1 lb. of oxygen + 3.32 lbs. of nitrogen = 4.32 lbs. of air.

Based on the approximate molecular weights, one pound of carbon will require

$$\frac{O_2}{C} = \frac{32}{12} = 2.666 \text{ lbs. of oxygen}$$

or 2.666 × 4.32 = 11.52 lbs. of air for complete combustion. The product formed will be carbon dioxide,

$$C + 2O = CO_2 \qquad 140$$

and the total weight of the gaseous products per pound of oxygen will be

$$1 + 11.52 = 12.52 \text{ lbs.}$$

Likewise, one pound of hydrogen will require

$$\frac{O}{H_2} = \frac{16}{2} = 8 \text{ lbs. of oxygen}$$

or 8 × 4.32 = 34.56 lbs. of air for complete combustion. The product formed is water (steam),

$$2H + O = H_2O \qquad 141$$

and the total weight of the gaseous products per pound of oxygen will be

$$1 + 34.56 = 35.56 \text{ lbs.}$$

Finally, one pound of sulphur will require

$$\frac{O_2}{S} = \frac{32}{32} = 1 \text{ lb. of oxygen}$$

or 1 × 4.32 = 4.32 lbs. of air for complete combustion. The product formed will be sulphur dioxide,

$$S + 2O = SO_2 \qquad 143$$

and the total weight of gaseous products per pound of oxygen will be

$$1 + 4.32 = 5.32 \text{ lbs.}$$

Whence, the total weight of dry air required per pound of fuel is equal to

$$W_{ta} = 11.52\ C + 34.56\ \left(H - \frac{O}{8}\right) + 4.32\ S \qquad 144$$

in which W_{ta} = weight in lbs. of dry air required per pound of fuel,

C = weight in lbs. of carbon per pound of fuel,

$H - \frac{O}{8}$ = weight in lbs. of available hydrogen per pound of fuel,

S = weight in lbs. of sulphur per pound of fuel.

The above analysis is based on the assumption that the distribution of the air will be so perfect that each particle of oxygen of the air will come in contact with a particle of carbon or available hydrogen, thereby forming perfect combustion. In practice, however, this does not take place, since it is impossible to effect a perfect distribution. In case there is an insufficient supply of air (oxygen), some of the hydrogen may escape unburned or some of the carbon may be only partly burned, forming carbon monoxide instead of carbon dioxide,

$$C + O = CO \qquad 145$$

Carbon monoxide, however, is a combustible gas and will burn when heated to its ignition point and also supplied with the required amount of air,

$$CO + O = CO_2 \qquad 146$$

In order to insure that no combustible gases escape up the chimney, it is necessary to supply an excess of air to the fuel so that complete combustion may take place and every particle of combustible matter is burned. The percentage of excess air, or the ratio of the air actually supplied per pound of combustible to that theoretically required is derived as follows:

Oxygen is accompanied by

$\frac{79}{21} = 3.76$ times its *volume* of nitrogen

The nitrogen content of the air required for combustion is equal to

$$N - 3.76\,O \qquad 147$$

Hence, the ratio of the air actually supplied to that theoretically required is equal to

$$R_a = \frac{N}{N - 3.76\,O} \qquad 148$$

in which R_a = ratio of air supplied per pound of combustible to that theoretically required.

In case all the carbon is burned to CO_2, the ratio will be equal to

$$R_a = \frac{N}{N - 3.76\left(O + \frac{1}{2}CO\right)} \qquad 149$$

In the above, N and O represent the percentage by *volume* of the nitrogen and oxygen, respectively, in the flue gases as given by the flue gas analysis.

Whence the total actual weight of dry air required per pound of fuel is equal to

$$W_{Ta} = W_{ta}\,R_a = \left[11.52\,C + 34.56\left(H - \frac{O}{8}\right) + 4.32\right] R_a \qquad 150$$

in which W_{Ta} = total actual weight of dry air required per pound of fuel.

Fig. 46 gives the theoretical weight of air required per pound of fuel (coal).

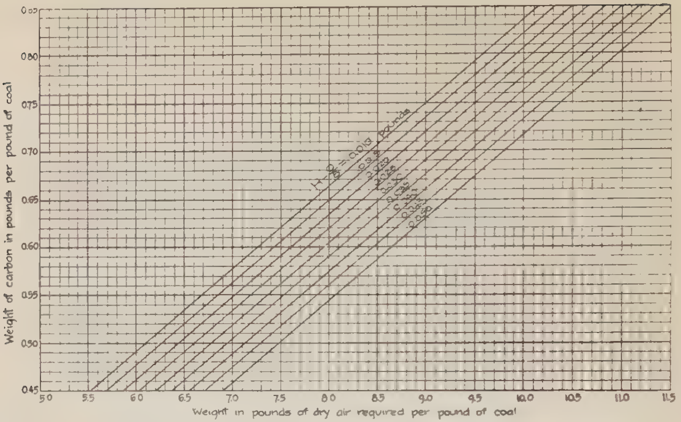

Fig. 46. Theoretical Weight of Air Required per Pound of Coal.

Based on $W_{ta} = 11.52 + 34.56 \left(H - \frac{0}{8}\right) + 4.32\ S$

Weight of sulphur neglected.

TABLE 12

Fuel	*Theoretical amount of air in pounds required per pound of fuel.*
Wood	6.0
Peat	7.3
Lignite	8.8
Sub-bituminous	10.2
Bituminous	10.7
Coke	10.8
Semi-bituminous	11.4
Semi-anthracite	11.6
Anthracite	11.7
Crude oil	14.4

Table 12 gives the approximate theoretical amount of air required to burn one pound of various fuels. These results are based on average typical analyses.

In general, however, the theoretical amount of air required to burn one pound of fuel varies between wide limits even with the same grade of fuel. It has been found, however, that there is a close agreement between most fuels when the theoretical air requirements are based on the calorific value of the fuel. This agreement is based on a theoretical air requirement of 7.4 pounds per 10,000 b.t.u. Whence:

$$W_{Ta} = 7.4\frac{\text{b.t.u.}}{10,000} \tag{151}$$

Excess Air Requirement

As stated before, in practice it is impossible to obtain perfect combustion with only the theoretical amount of air as calculated. This is due to impurities in the fuel and the practical impossibility of getting a particle of oxygen (air) in contact with a particle of carbon (fuel). As a consequence an excess of the theoretical amount of air is required. This excess may be computed from equations 148 and 149. In practice, however, the amount of excess air admitted is arbitrarily regulated by the amount of CO_2 desired in the chimney gases. Fig. 47 gives the relation between the CO_2 content in the gases and the excess air expressed in per cent of the theoretical minimum.

The amount of excess air admitted as expressed by the CO_2 content of the flue and chimney gases is a very important factor in chimney design and

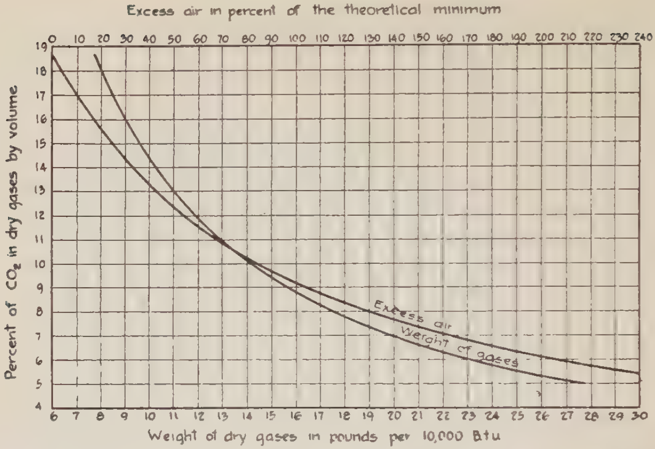

Fig. 47. Relation of excess air and weight of gases to percentage of CO_2.

performance, for upon it depend the amount of gases generated and also the temperature of the gases. The per cent of CO_2 decreases as the percentage of excess air increases, and the temperature of the flue and chimney gases also decreases as the percentage of excess air increases. It has been found by experience that a CO_2 content of approximately 13 per cent, which corresponds to an excess air percentage of approximately 50 per cent, gives the best results. Less than this amount will result in more or less incomplete combustion, while a greater amount will result in a lower gas temperature.

Weight of products of combustion per pound of fuel

Then the total weight of the products of combustion per pound of fuel is equal to

$$W_{tp} = W_{ta} + C + \left(H - \frac{O}{8}\right) + S \qquad 152$$

in which W_{tp} = total weight in lbs. of products of combustion per pound of fuel.

Based on an analysis of the flue gases, the theoretical amount of air required per pound of fuel is equal to

$$W_{ta} = 34.56 \left(\frac{C}{3} + \left(H - \frac{O}{8}\right) + \frac{S}{8}\right) \qquad 153$$

in which C, H, and S represent the percentage by *weight* of carbon, hydrogen, and sulphur in the fuel.

The weight of the flue gases per pound of carbon is equal to

$$\frac{11\ C\ O_2 + 8\ O + 7\ (CO + N)}{3\ (CO_2 + CO)} \qquad 154$$

in which CO_2, O, CO, and N are the percentages by volume as determined by the flue gas analysis. Whence, the total weight of the products of combustion per pound of fuel is equal to

$$W_{tp} = \frac{11\ CO_2 + 8\ O + 7\ (CO + N)}{3\ (CO_2 + CO)}\ C + \frac{S}{1.83} \qquad 155$$

in which C and S are the percentages by *weight* of carbon and sulphur contained in the fuel.

Total weight of products of combustion

Let G = total grate surface of boilers in square feet,

and C_g = pounds of coal burned per square foot of grate surface per hour.

Then $C_g G$ = total amount of coal burned in lbs. per hour.

Whence, the total weight of the products of combustion is equal to

$$W_{Tp} = C_g G \left(W_{ta} + C + \left(H - \frac{O}{8}\right) + S\right) \text{ lbs. per hour} \qquad 156$$

If the gases passing up the chimney have the same temperature as those leaving the boiler,

$$W_a = \frac{W_{Tp}}{3600} = \frac{C_g G \left(W_{ta} + C + \left(H - \frac{O}{8}\right) + S\right)}{3600} \qquad 157$$

Likewise

$$W_a = \frac{W_{Tp}}{3600} = \frac{C_g\ G \left(\frac{11\,CO_2 + 8\,O + 7(CO + N)}{3\,(CO_2 + CO)}\ C + \frac{S}{1.83}\right)}{3600} \qquad 158$$

W_{Tp} = total amount of products of combustion formed per hour.

W_a = total amount of gases leaving the boiler and passing up the chimney per second.

Fig. 48 gives the total products of combustion formed per second for various amounts of air.

Density of the gases

In determining the theoretical draft and the various losses of draft, and also the capacity, of a working chimney, it is necessary to know the

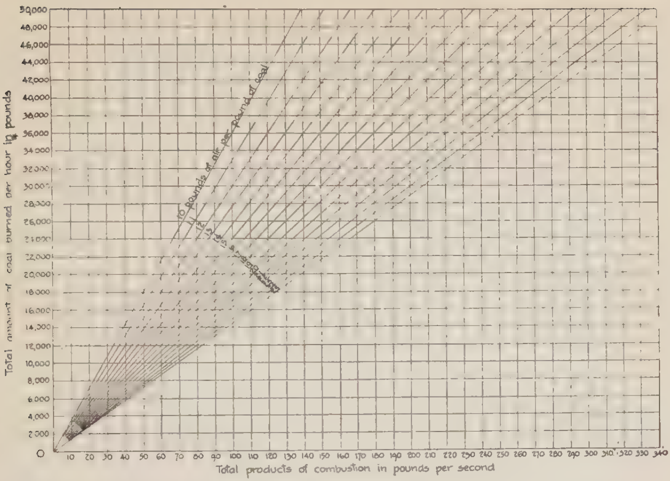

Fig. 48. Total Products of Combustion per Second for Various Amounts of Air.

weight of the gases per cubic foot, W_c, at a certain temperature which, in this book, is always taken at 32 degrees Fahr. The weight of a cubic foot of dry air is equal to 0.08071 pounds at 32 degrees Fahr. and this weight is often used as the weight of the chimney gases. This unit, however, is not strictly true since the products of combustion are always heavier than air. The weight of the gases as they leave the boiler ranges between 0.082 to 0.088 pounds per cubic foot at 32 degrees Fahr. Draft and capacity calculations based on the assumption that the density of the chimney gases is the same as that of the outside air will give results which are greatly in excess of the actual figures.

The unit weight, or density, of the flue and chimney gases is based on the CO_2, O_2, and N_2 content. The density of the gases in pounds per cubic foot at 32 degrees Fahr. is given by the equation:

$$W_c = 0.123\ CO_2 + 0.089\ O_2 + 0.078\ N_2 \qquad 159$$

in which CO_2, O_2, and N_2 represent the percentages of the parts by weight of these gases in the products of combustion. For example: If an analysis of the gases showed 10 per cent CO_2, 12 per cent O_2, and 78 per cent N_2, then

$$W_c = 0.123 \times .10 + 0.089 \times .12 + 0.078 \times .78$$
$$= 0.0838$$

This figure represents the density, or the weight in pounds per cubic foot, at 32 degrees Fahr. This figure is the starting point of the analysis of all draft and capacity problems.

In designing a new chimney, it is of course impossible to predict the density of the gases with any degree of accuracy. However, it has been found by experiment that a fair average for the density of the chimney gases is 0.0855 pounds per cubic foot at 32 degrees Fahr. and this figure has been used throughout the problems in the book in the absence of any definite data.

Smoke

Smoke is unburned carbon in a flocculent state together with ash and is produced in the furnace when the incandescent particles of carbon are cooled before coming in contact with the proper amount of oxygen which should unite with them. Smoke is usually associated with bituminous coals.

Temperature of gases

As the gases leave the combustion chamber and pass on through the boiler, the latter absorbs all the heat possible from them and transmits it to the water and steam. The temperature of the water in the boiler limits the extent to which this cooling process can be carried on, and for this reason the temperature of the gases as they leave the furnace should be as high as possible. In average practice the temperature of the gases as they leave the furnace ranges between 2500 and 3000 degrees Fahr. when the furnace is being operated economically. The latter temperature may be attained for high rates of combustion with a relatively low percentage of excess air. As a general rule, such temperatures are encountered for only short intervals. When a boiler is being operated at a low rating, the temperature of the gases may be as low as 1500 degrees Fahr. and particularly so during inefficient operation.

The temperature of the gases as they enter the breeching varies between wide limits but will average between 500 and 650 degrees Fahr., except in the cases when an economizer is used when the gas temperature may be as low as 350 to 400 degrees Fahr. Inasmuch as the draft and capacity, as well as the required height and diameter, of a chimney varies as the temperature of the gases, it is of utmost importance that a figure for this value be selected with the utmost caution. When an economizer is used, the figure selected should be considerably less than when none is used. In the absence of any definite data, the temperature of the flue and chimney gases may be taken at 450 degrees Fahr. when an economizer is used and at 550 to 600 degrees Fahr. for ordinary installation. Fig. 49 gives the probable temperature of the flue and chimney gases in terms of the number of pounds of water evaporated per square foot of heating surface per hour.

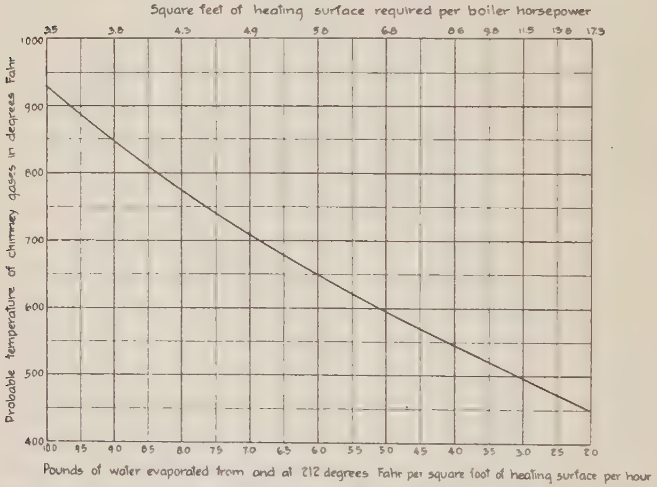

Fig. 49. Probable temperature of chimney gases for various amounts of water evaporated.

Much has been written and conjectured concerning the temperature drop as the chimney gases ascend in the chimney. One authority states that the temperature of the gases in the chimney decreases about 1 degree Fahr. per foot of chimney. Another writer has arbitrarily based the average temperature of the chimney gases on the height and diameter of the chimney, using a multiplying factor based on the per cent of the entering temperature of the gases. Neither of these methods give satisfactory results since the type of chimney and other controlling factors are not taken into consideration. It is the writer's contention that, if a chimney is properly constructed and properly lined, the temperature drop will not be of much consequence. When investigating the performance of a working chimney, the average chimney gas temperature may be observed by means of a pyrometer. In the case of a new chimney which is being designed, the value of the chimney gas temperature selected is purely a matter of arbitrary choice by the designer.

CHAPTER VIII

THEORY OF CAPACITY

The capacity of a chimney is measured by the amount of gases it will discharge during a stated interval of time. The oxygen of the air unites with the fuel in the combustion chamber and gases are formed with a certain temperature. These gases in turn pass on through the boiler, through the breeching, and then into, and out through, the chimney, finally dissipating themselves into the upper regions. It can be easily understood how ordinary gases will flow in a horizontal duct, even though they are of the same temperature as, but with a different density from, that of the outside air. But in the case of chimney gases, the temperature is enormously higher and the density slightly greater than that of the atmosphere; and, in addition, the gases, instead of flowing horizontally, pass up a vertical duct and flow against gravity. Since the temperature of the chimney gases is greater than that of the outside air, the former, being considerably lighter in weight per unit volume, will rise just as a balloon, which is full of hot gases or air, rises in the surrounding cooler atmosphere. In developing the theory for the capacity of a chimney, however, it is necessary to have more information at hand than the mere fact that the gases simply go up the chimney. There must be some impelling force that imparts velocity to the gases. This will now be discussed in detail.

The actual amount of gases generated in a boiler furnace can be computed with a relatively fair degree of accuracy. In determining the amount of gases it is necessary to know the kind of coal which is being burned, together with an analysis of its constituents, and also the rate of combustion and the total area of the grate surface.

The theoretical amount of air required to burn one pound of fuel is determined from an analysis of the coal and is given by equation 144. Multiplying this value by the excess air percentage required will give the actual amount of air required as given by equation 150. To this product is added the weight of the carbon, available hydrogen, and sulphur per pound of coal. Multiplying this result by the product of the number of square feet of grate surface and the rate of combustion, and dividing by 3600 will give the amount of gases generated per second.

After the gases have been formed or generated in the combustion chamber, they pass on through the rest of the boiler, through the breeching and chimney, and finally out into the upper regions. As stated in Chapter I, a chimney may be considered as a sort of a pump whose function is to pump hot gases. Hence, a chimney does work on the gases. A chimney "pumping" gases through a steam plant installation is analagous to a water pump pumping water through a waterworks system, with this essential difference, however, that temperature has practically no effect on the latter but is an important factor in the former.

Practically, the capacity of a chimney expressed in cubic feet per second is equal to the area of the chimney in square feet multiplied by the velocity of the chimney gases in feet per second.

$$Q = AV \qquad 160$$

Now from equation 8:

$$Q = \frac{WRT_c}{P_o} \qquad 161$$

Whence, the theoretical capacity of a chimney expressed in pounds of gases passing per second, from equations 160 and 161, equals

$$\frac{WRT_c}{P_o} = AV$$

and $$W = \frac{AVP_o}{RT_c} \qquad 162$$

Now $$R = \frac{P}{W_c T} \qquad 163$$

Then $$W = \frac{A V W_c T P_o}{T_c P} = 33.44 \frac{A V W_c P_o}{T_c} = 16.43 \frac{A V W_c B_o}{T_c} \qquad 164$$

In equation 164, the term V denotes the velocity of the *chimney gases* in feet per second. It should be stated here with much emphasis that the velocity of the gases in the chimney is not the same as the velocity of the gases in the furnace or the boiler, and, moreover, bears no relation to the latter. When the hot gases enter the chimney, it is said that they rise of their own accord, because they are lighter in weight, or are pushed up because the cooler outside air is heavier in weight.

Since the gases move and therefore have velocity, it is necessary that they be given some impelling force. What is this impelling force and to what is it due?

Two lines of thought have been developed as to the cause of this impelling force in the production of velocity: first, that velocity is due to gravity alone, and second, that velocity is due to the expenditure of heat. The first may be called the mechanical theory and the second the thermodynamical theory of the production of velocity of the chimney gases. The following analysis will be based on the thermodynamical theory of the production of velocity.

Velocity, then, is due to the expenditure of heat and is produced by creating a difference in pressure, which in turn is produced by a difference in weight between the outside air and the hot gases inside the chimney.

Let V_t = theoretical velocity of chimney gases in feet per second

Also let h = head in feet producing velocity

Then hd_c = weight of column of chimney gases producing the velocity

$$= Hd_o - Hd_c \qquad 165$$

Or $$hW_c \frac{T}{T_c} = HW_o \frac{T}{T_o} - HW_c \frac{T}{T_c} \qquad 166$$

Whence $$h = H \left(\frac{W_o}{W_c}\frac{T_c}{T_o} - 1\right) \qquad 167$$

Now $$V_t = \sqrt{2gh} \qquad 168$$

Whence $$V_t = \sqrt{2gH\left(\frac{W_o}{W_c}\frac{T_c}{T_o} - 1\right)} \qquad 169$$

Let $$\frac{W_o}{W_c} = C_t \tag{170}$$

$$V_t = 8.02\sqrt{H\left(\frac{C_t\,T_c}{T_o} - 1\right)} \tag{171}$$

Fig. 50 gives the theoretical velocity of the chimney gases for various values of chimney gas temperature, outside air temperature, and height of chimney.

It should be noted in particular, and borne in mind constantly, that the velocities, as given by equations 169 and 171, and also by Fig. 50, are theoretical values only, since they are based on the assumption that the gases are flowing through a frictionless duct. In practice, however, the actual velocities are considerably less than the theoretical values on account of the retardation due to friction. The ratio between the actual and the theoretical velocities will be taken up in detail in a subsequent paragraph.

From equations 160 and 171, the theoretical capacity of a chimney, expressed in cubic feet per second, is equal to

$$Q = A\sqrt{2gH\left(\frac{C_t\,T_c}{T_o} - 1\right)} \tag{172}$$

Likewise, from equations 164 and 171, the theoretical capacity of a chimney, expressed in pounds of chimney gases passing per second, is equal to

$$W_t = 33.44\,\frac{A\,W_c\,P_o}{T_c}\sqrt{2gH\left(\frac{C_t\,T_c}{T_o} - 1\right)} \tag{173}$$

$$= 33.44\;A\,W_c\,P_o\sqrt{2gH\left(\frac{C_t\,T_c - T_o}{T_o\,T_c^2}\right)} \tag{174}$$

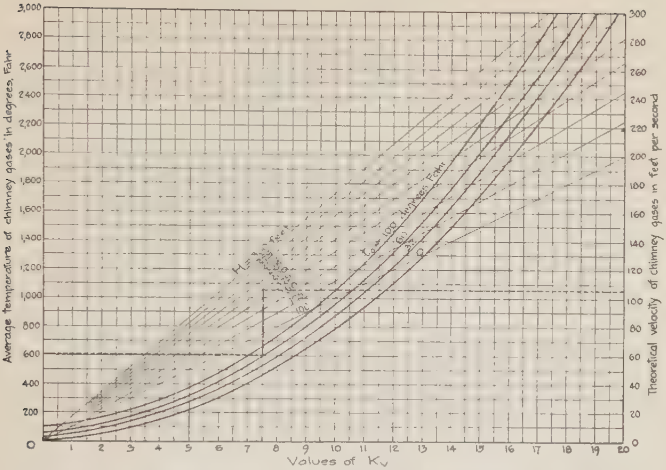

Fig. 50. Theoretical Velocities of Chimney Gases Based on a Chimney Gas Density of 0.0855 Pound per Cubic Foot at 32 Degrees Fahr., or $\frac{W_o}{W_c} = 0.944$.

$$= 268.2\, A\, W_c\, P_o \sqrt{H \left(\frac{C_t\, T_c - T_o}{T_o\, T_c^2}\right)} \qquad 175$$

in which W_t = theoretical capacity of the chimney gases in pounds per second.

Equation 175 gives the theoretical capacity of a chimney expressed in terms of pounds of gases passing per second in a frictionless duct. If there were no retardation of the gases going up the chimney, due to friction, the actual velocity of the chimney gases would be equal to the theoretical velocity, and the actual capacity or the actual amount of gases discharged or passing per second would be equal to the theoretical amount, as given by equation 175. Such, however, is not the case, since there is considerable retardation of the velocity of the gases as they ascend. It, therefore, becomes necessary to establish a relation between the actual and the theoretical velocity and also between the actual capacity and the theoretical capacity.

Let $R_v = \frac{V_a}{V_t}$ 176

in which V_a = working velocity of the chimney gases in feet per second

and R_v = ratio of actual velocity to theoretical velocity

Whence $V_a = R_v V_t$ 177

$= R_v \sqrt{2gH\left(\frac{C_t T_c}{T_o} - 1\right)}$ 178

Likewise, let

$R_c = \frac{W_a}{W_t}$ 179

in which W_a = actual capacity of the chimney in pounds of gases passing per second.

and R_c = ratio of actual capacity to theoretical capacity

Whence $W_a = R_c W_t$ 180

$= 268.2\, R_c\, A\, W_c\, P_o \sqrt{H\left(\frac{C_t T_c - T_o}{T_o T_c^2}\right)}$ 181

Let $K_c = 268.2\, W_c\, P_o \sqrt{H\left(\frac{C_t T_c - T_o}{T_o T_c^2}\right)}$ 182

Then $W_a = R_c A K_c$ 183

Fig. 51 gives the values of K_c for various values of chimney gas temperature and height of chim-

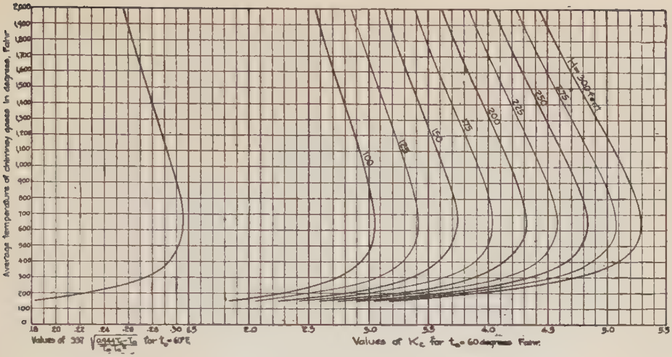

Fig. 51. Values of Capacity Constant K_c.

$$K_c = 268.2 W_c P_o \sqrt{H\left(\frac{C_t\, T_c - T_o}{T_o T_c^2}\right)}$$

Based on sea level atmospheric conditions and $W_c = 0.0855$ or $C_t = 0.944$.

ney, based on an outside air temperature of 60 deg. Fahr., $W_c = 0.0855$, and $P_o = 14.7$. The curves were computed from equation 182.

Fig. 52 gives the theoretical capacity of a chimney for various areas and various values of K_c, and also the actual capacity for various values of R_c. These curves were computed from equation 183, and are based on an outside air temperature of 60 deg. Fahr.

It should be noted that both Fig. 51 and Fig. 52 are based on a chimney gas density of 0.0855 lbs. per cu. ft. at 32 deg. Fahr., or

$$C_t = \frac{W_o}{W_c} = \frac{0.08071}{0.0855} = 0.944$$

From Fig. 51, it will be seen that the capacity of

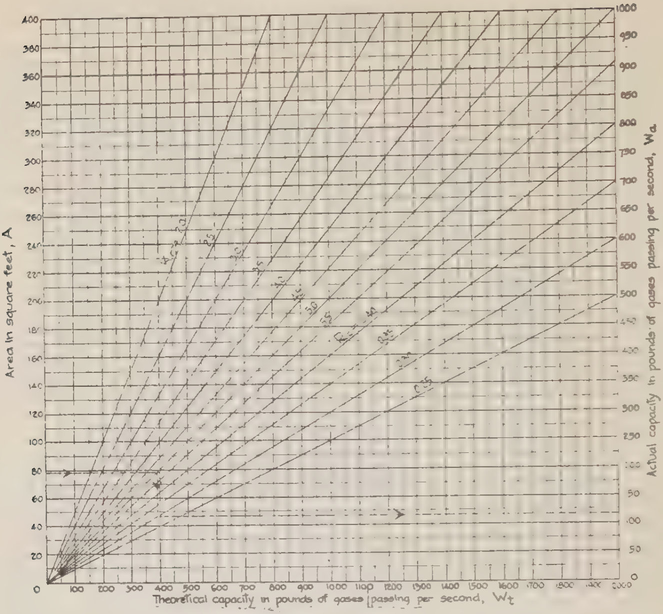

Fig. 52. Theoretical and Actual Capacity of Chimneys. Based on $W_t = AK_c$ and $W_a = R_cAK_c$

Sea level atmospheric conditions, chimney density of 0.0855, and outside air temperature of 60 deg. Fahr.

a chimney gradually increases as the temperature of the chimney gases increases, until a maximum is reached at a chimney gas temperature of about 640 deg. Fahr., after which the capacity gradually decreases but at a much lower ratio than the increase. The turning point of 640 deg. Fahr. occurs when the temperature of the outside air is 60 deg. Fahr. and the density of the chimney gases is equal to 0.0855 lbs. per cu. ft. at 32 deg. Fahr.

The turning point of the curve represents the maximum capacity of the chimney and varies with the temperature of the outside air and the density of the chimney gases.

Fig. 56 gives the capacity of a chimney in terms of pounds of gases discharged or moved per second, for various values of A, R_c, K_t, and H, based on the conditions as noted. The values of K_t for three values of outside air temperature and two values of chimney gas density for various chimney gas temperatures are also indicated. In using this chart, the values of K_t and R_c should first be corrected for the proper chimney gas density.

Maximum Capacity

In equation 175, the variation due to changes in the temperature of the chimney gases and also the temperature of the outside air may be represented by the equation

$$K_t = \sqrt{\frac{C_t T_c - T_o}{T_o T_c^2}} \qquad 184$$

in which $C_t = \frac{W_o}{W_e}$ 185

Fig. 53 gives the value of K_t for various chimney gas temperatures and outside air temperatures, based on $C_t = 1.00$, or a chimney gas density of 0.08071 lbs. per cu. ft. at 32 deg. Fahr. The curves show that the value of K_t increases until a certain chimney gas temperature is reached after which K_t decreases in value. For an outside air temperature of 60 deg. Fahr., for example, K_t in-

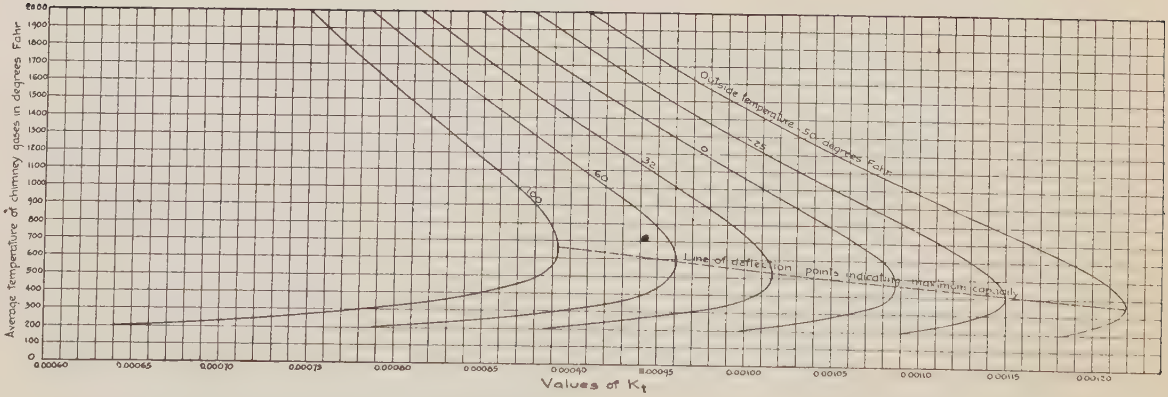

Fig. 53. Curves of $K_t = \sqrt{\dfrac{C_t T_c - T_o}{T_o T_t^2}}$ in capacity equation together with line of deflection points indicating maximum capacity.

Based on $W_c = W_o = 0.08071$ or $C_t = 1.00$

creases until a chimney gas temperature of 580 deg. Fahr. is reached after which its value decreases.

Equation 181 may be written

$$W_a = 268.2\, W_c\, A\, R_c\, P_o\, K_t \sqrt{H} \qquad 186$$

Hence, the actual capacity of the chimney is affected directly by the value of K_t, decreasing as K_t decreases and increasing as K_t increases.

It is obvious that the turning points of the curves represent the figure (chimney gas temperature) at which the chimney will attain its maximum capacity, or, in other words, the maximum quantity of gases will be discharged at a chimney gas temperature represented by the turning points. The turning points of the curves as represented by the chimney gas temperatures vary as the temperature of the outside air and also as the density of the chimney gases, the representation in degrees decreasing as the temperature of the outside air decreases, but increasing as the density of the chimney gases increases. Thus, from Fig. 53 it will be seen that for a chimney gas density of 0.08071 lbs. per cu. ft. at 32 deg. Fahr., the turning point occurs at a chimney gas temperature of 580 deg. Fahr. and consequently the maximum capacity of the chimney will be attained at that temperature. For an outside air temperature of 100 deg. Fahr., however, the maximum is reached at a chimney gas temperature of 660 deg. Fahr., and for an outside air temperature of 0 deg. Fahr., at a chimney gas temperature of only

460 deg. Fahr. Again, for a chimney gas density of 0.0855 lbs. per cu. ft. at 32 deg. Fahr., the maximum will be reached at a chimney gas temperature of 642 deg. Fahr. for an outside air temperature of 60 deg. Fahr., at 727 deg. Fahr. for an outside air temperature of 100 deg. Fahr., and at only 515 deg. Fahr. for an outside air temperature of 0 deg. Fahr.

The turning points of the curves are found by finding the derivative of the function, placing equal to zero, and solving the resulting equation. The first derivative of equation 184 is equal to:

$$\frac{dK_t}{dT_c} = \tfrac{1}{2}\left(\frac{C_tT_c - T_o}{T_oT^2_c}\right)^{-\frac{1}{2}} \frac{d}{dT_c}\left(\frac{C_tT_c - T_o}{T_oT^2_c}\right) \qquad 187$$

$$= \tfrac{1}{2}\left(\frac{T_oT^2_c}{C_tT_c - T_o}\right)^{\frac{1}{2}} \times \left(\frac{C_tT_oT^2_c - (C_tT_c - T_o)\,2T_oT_c}{T^2_oT^4_c}\right) \qquad 188$$

$$= \tfrac{1}{2}\left(\frac{T_oT^2_c}{C_tT_c - T_o}\right)^{\frac{1}{2}} \times \left(\frac{C_tT_c - 2C_tT_c + 2T_o}{T_oT^3_c}\right) \qquad 189$$

Now when $\frac{dK_t}{dT_c} = 0$, then K_t is a maximum

Then $$\tfrac{1}{2}\left(\frac{T_oT^2_c}{C_tT_c - T_o}\right)^{\frac{1}{2}} \times \left(\frac{C_tT_c - 2C_tT_c + 2T_o}{T_oT^3_c}\right) = 0 \qquad 190$$

Whence $$C_tT_c - 2C_tT_c + 2T_o = 0 \qquad 191$$

and $$+C_tT_c = +\,2T_o \qquad 192$$

and finally $$T_c = \frac{2T_o}{C_t} = \frac{2\,T_o\,W_c}{W_o} \qquad 193$$

Therefore, K_t, and also the capacity of a chimney, is a maximum when the *absolute* temperature of the chimney gases is equal to twice the *absolute* temperature of the outside air divided by the *ratio* of the density of the outside air to the density of the chimney gases.

This chimney gas temperature at which a chimney will attain its maximum capacity is of great importance in chimney design. It will be seen that for an outside air temperature of 60 deg. Fahr., the maximum ranges from 580 deg. Fahr. for a chimney gas density of 0.08071 lbs. per cu. ft. at 32 deg. Fahr. to 642 deg. Fahr. for a chimney gas density of 0.0855 lbs. per cu. ft. at 32 deg. Fahr. Both above and below these figures, the capacity gradually decreases as the chimney gas temperature increases and diminishes. An inspection of Fig. 53 will show that the value of K_t, and the capacity of the chimney, decreases at a greater rate when the chimney gas temperature drops below the maximum figures than when it rises above the same figures. From the standpoint of economy, then, it is well to keep the temperature of the chimney gases as near as possible to the above figures depending upon the density of the gases. Fig. 54 gives the chimney gas temperatures at which the maximum is attained for various values of outside air temperatures and chimney gas densities.

Example: Determine the chimney gas temperature at which a chimney will attain its maximum capacity when the temperature of the outside air is 60 deg. Fahr. and the density of the chimney gases is equal to 0.0855 lbs. per cu. ft. at 32 deg. Fahr.

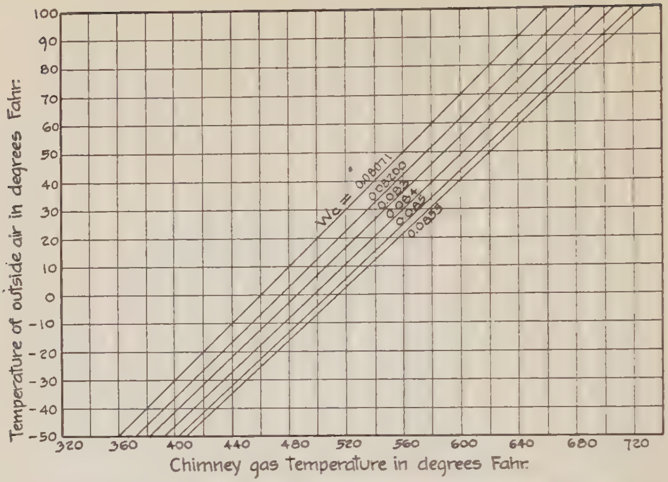

Fig. 54. Chimney gas temperatures for maximum capacity.

Based on equation $K_t = \sqrt{\frac{C_tT_c - T_o}{T_oT_c^2}}$

K_t is a maximum when $T_c = \frac{2T_o}{C_t}$

From equation 185:

$$C_t = \frac{0.08071}{0.0855} = 0.944$$

Then from equation 193:

$$T_c = \frac{2 \times 519.6}{0.944} = 1100.8 \text{ deg. Fahr. absolute}$$

Whence $t_c = 1100.9 - 459.6 = 641.2$ deg. Fahr.

If the temperature of the outside air is equal to 100 deg. Fahr.,

$$T_c = \frac{2 \times 559.6}{0.944} = 1185.6 \text{ deg. absolute}$$

Whence $t_c = 1185.6 - 459.6 = 726$ deg. Fahr.

The R_c Factor

An inspection of equation 181 will disclose the fact that the values of all of the various factors may be readily ascertained with the exception of R_c. The quantity R_c is a very important factor entering into the equation for the capacity of a chimney, yet very little attention is ordinarily paid to its value. This factor is usually referred to as the *efficiency* of the chimney and values of from 0.25 to 0.35 have been assigned to it to express the relation between the actual and the theoretical amount of gases discharged by the chimney regardless of the many factors entering into its makeup.

It is obvious that, since the capacity of a chimney varies as the velocity of the gases, the ratio of the actual capacity to the theoretical capacity should vary as the ratio of the actual or working velocity to the theoretical velocity. Whence:

$$R_c = R_v = \frac{W_a}{W_t} = \frac{V_a}{V_t} \qquad 194$$

Fig. 55 gives the value of R_c for various values of V_a and V_t.

It is now necessary to establish some relation between the actual or working velocity and the theoretical velocity of the chimney gases.

The fundamental equation for the loss of draft due to velocity as noted in Chapter III is as follows:

$$h_v = 0.1923\ W_c\ \frac{P\ T\ V^2_a}{P_o\ T_c\ 2g} \qquad 195$$

Whence $$V_a = \sqrt{\frac{P_o\, T_c\, 2g\, h_v}{0.1923\, W_c\, P\, T}} \qquad 196$$

Now since $2g = 64.4$
$P = 14.7$
and $T = 491.6$

Then $$V_a = 0.215 \sqrt{\frac{P_o\, T_c\, h_v}{W_c}} \qquad 197$$

Whence, from equations 171 and 197:

$$R_c = \frac{0.215 \sqrt{\dfrac{P_o\, T_c\, h_v}{W_c}}}{8.02 \sqrt{H \left(\dfrac{C_t\, T_c}{T_o} - 1 \right)}} \qquad 198$$

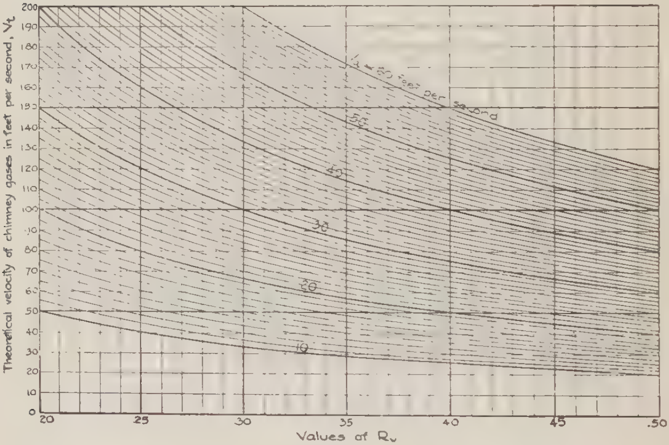

Fig. 55. Relation of Actual Velocity of Chimney Gases to Theoretical Velocity.

These curves may be used also in determining the value of R_c.

$$= 0.0268 \frac{\sqrt{\frac{P_o T_c h_v}{W_c}}}{\sqrt{H\left(\frac{C_t T_c}{T_o} - 1\right)}} \qquad 199$$

Example

Determine the capacity of a chimney from the following data:

150 ft., height of chimney,
6 ft., diameter of chimney,
600 deg. Fahr., temp. of the chimney gases,
60 deg. Fahr., temperature of outside air,
0.0855 density of the chimney gases.
Sea level atmospheric conditions.
Assume $h_v = 0.10$ inches of water.

Now from equation 199:

$$R_c = 0.0268 \frac{\sqrt{\frac{14.7 \times 1059.6 \times 0.10}{0.0855}}}{\sqrt{150\left(\frac{0.944 \times 1059.6}{519.6} - 1\right)}}$$

$$= 0.306$$

From equation 182:

$$K_c = 3942 \times 0.0855 \times \sqrt{150 \frac{0.944 \times 1059.6 - 519.6}{(519.6)\ (1059.6)^2}}$$

$$= 3.75$$

Finally, from equation 183:

$$W_a = 28.3 \times 3.75 \times 0.306$$
$$= 32.6 \text{ pounds per second.}$$

It will be noted that all of the conditions can be ascertained with the exception of the loss of draft due to velocity. The intensity of the working velocity is controlled by the intensity of this loss of draft. It will be developed in a later chapter that an economical velocity will be obtained when the loss of draft due to velocity is assumed at approximately 0.10 inches of water.

For a chimney gas density of 0.0855 pounds per cubic foot and an outside air temperature of 60 deg. Fahr., the chimney will attain its maximum capacity when the temperature of the chimney gases is equal to 641.2 degrees Fahr. as noted in the example on page 194. In this case the capacity of the chimney is computed as follows:

From equation 184:

$$K_t = \sqrt{\frac{0.944 \times 1100.8 - 519.6}{(519.6)\ (1100.8)^2}}$$

$$= 0.000908$$

$$R_c = 0.0268\ \frac{\sqrt{\dfrac{14.7 \times 1100.8 \times 0.10}{0.0855}}}{\sqrt{150\left(\dfrac{0.944 \times 1100.8}{519.6} - 1\right)}}$$

$$= 0.302$$

Finally, from equation 186:

$$W_a = 268.2 \times 0.0855 \times 28.3 \times 0.302 \times 0.000908 \times 14.7 \times 12.25$$

$$\doteq 33 \text{ pounds per second}$$

Capacity Based on Horsepower Equivalent

In coal fired installations, it is quite convenient to express the capacity of a chimney in terms of the horsepower equivalent of the boilers.

Let W_{ta} = lbs. of air required per lb. of coal for complete combustion,

and C_{bh} = lbs. of coal burned per b.h.p. per hour.

Then $W_{bh} = W_{ta}C_{bh}$ = lbs. of gases formed per b.h.p. per hour.

$$\text{Whence H.P.} = \frac{W_a}{\frac{W_{bh}}{3600}} = \frac{3600 W_a}{W_{bh}} \qquad 200$$

$$= 965{,}520 \frac{R_c\, A\, W_c\, P_o}{W_{bh}} \sqrt{H \left(\frac{C_t T_c - T_o}{T_o T_c^2}\right)} \qquad 201$$

$$= 965{,}520 \frac{R_c\, A\, W_c\, P_o\, K_t \sqrt{H}}{W_{bh}} \qquad 202$$

in which H.P. = horsepower equivalent of the chimney.

It should be noted clearly that equation 202 gives the *equivalent* horsepower of a chimney. A b.h.p. is defined as the equivalent of the evaporation of 34.5 lbs. of water per hour from a temperature of 212 deg. Fahr. to steam at atmospheric pressure. The horsepower equivalent of a chimney is equal to the total weight of gases passing per second divided by the amount of gases formed per boiler horsepower per second. Expressing the capacity of a chimney in terms of the horsepower equivalent is done for convenience. A direct reference as to general requirements can then be made from the horsepower of the boiler to the equivalent horsepower of the chimney.

In equation 202, for a chimney gas temperature of 642 deg. Fahr., an outside air temperature of 60 deg. Fahr., and a chimney gas density of 0.0855 lbs. per cu.ft. at 32 deg. Fahr., and $P_o = 14.7$,

$K_t = 0.000908$

and $$\text{H.P.} = 1100 \frac{R_c A \sqrt{H}}{W_{bh}} \qquad 203$$

For a circular section based on the diameter,

$$\text{H.P.} = 864 \frac{R_c D^2 \sqrt{H}}{W_{bh}} \qquad 204$$

Fig. 57 gives the horsepower equivalent of a chimney for various values of R_c, W_{bh}, D, and H, based on the conditions as noted.

Use of Charts

Figs. 56 and 57 will be found quite useful for determining the capacity of a chimney, based on lbs. of gases discharged or moved per second and horsepower equivalent, respectively. The curves for Fig. 56 are based on the equation

$$W_a = 268.2\, A R_c W_c P_o K_t \sqrt{H}$$

The dotted lines show how the capacity is found graphically for the example given on page 197. Entering the chart at the left hand side at a chimney gas temperature of 600 deg. Fahr., a straight line is then traced to the intersection of the curve for $t_o = 60$ deg. Fahr. and $W_c = 0.0855$, thence downward until the line for $R_c = 0.306$ is reached, thence to the right to the intersection of the line for H = 150 ft. 0 in., thence downward to the intersection of the line for A = 28.3, and finally to the right where the capacity is found to be 33 lbs. per second.

The curves for Fig. 57 are based on the equation

$$H.P. = 864 \frac{R_c D^2 \sqrt{H}}{W_{hh}}$$

and are for a chimney gas temperature of 642 deg. Fahr. and an outside air temperature of 60 deg. Fahr. A chimney gas density of 0.0855 lbs. per cu. ft. at 32 deg. Fahr. has also been assumed. The dotted line shows how the capacity is determined graphically for the same example as noted above, but with the additional factor that the furnace generates 100 lbs. of gases per horsepower per hour. Entering the chart at the bottom and to the right at a value of 100 for W_{hb}, a straight line is then traced to the intersection of the curve for $R_c = 0.306$, thence to the right to the intersection of the line for H = 150 ft. 0 in., thence downward to the intersection of the line for D = 6 ft. 0 in., and finally to the right where the capacity of the chimney is found to be approximately 1150 horsepower equivalent. It should be noted that the values for the horsepower equivalent as determined by the chart are based on a chimney gas temperature of 642 deg. Fahr. and an outside air temperature of 60 deg. Fahr. Any variation from these arbitrarily selected factors should be corrected.

Both charts are also based on sea level atmospheric conditions.

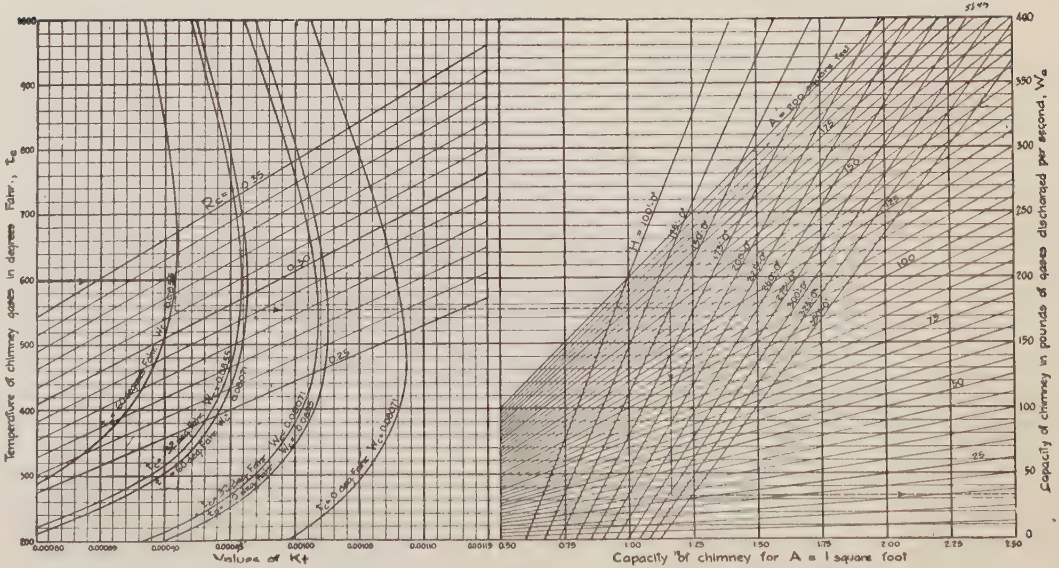

Fig. 56. Chart for determining the capacity of a chimney in terms of lbs. of gases discharged per second.

$W_a = 268.2\, A\, R_c\, W_c\, P_c\, K_t \sqrt{\frac{H.}{\ }}$ Based on sea level atmospheric conditions.

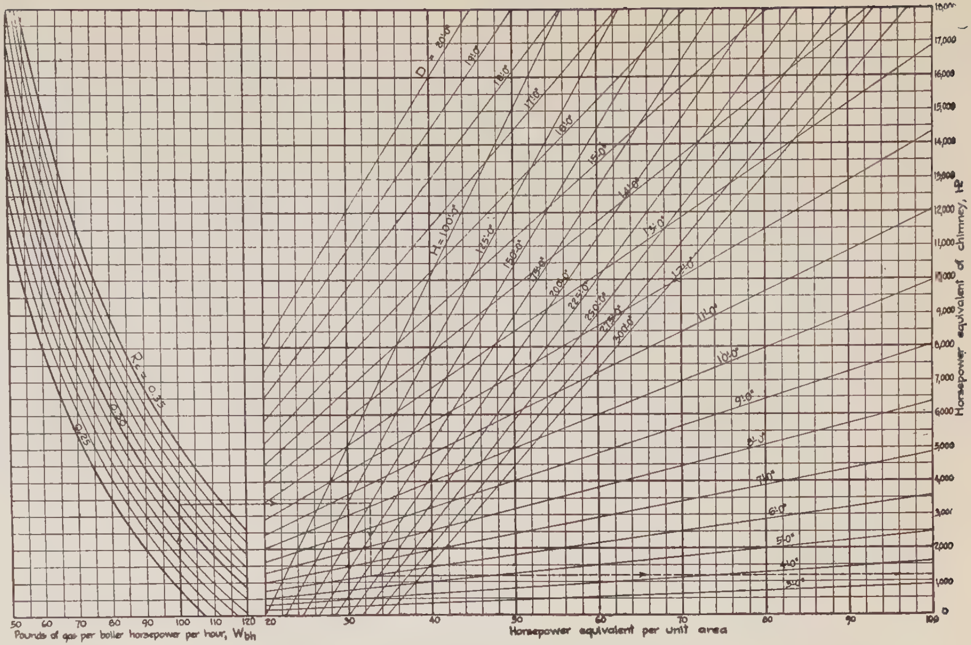

Fig. 57. Chart for determining the capacity of a chimney in terms of horsepower equivalent.

$$\text{H.P.} = 864 \; \frac{R_c D^2 \sqrt{H}}{W_{bh}} \quad \text{Circular section.}$$

Based on a chimney gas temperature of 642 deg. Fahr., an outside temperature of 60 deg. Fahr., a chimney gas density of 0.0855 lbs. per cu.ft. at 32 deg. Fahr., and sea-level atmospheric conditions.

CHAPTER IX

THE DIAMETER OR AREA OF THE CHIMNEY

The theory for the capacity of an existing or "working" chimney was developed in detail in Chapter VIII under the assumption that the chimney itself was of sufficient size to accommodate and pass economically all of the gases generated by the furnace. In other words, it was assumed that the chimney was of such a height that it produced sufficient draft to overcome all of the draft losses or resistances offered to the gases as they passed through the installation, and that the diameter was sufficiently large so that the gases would be properly discharged under the conditions for which the structure was designed. It was also assumed that the chimney was working at actual capacity.

It was shown that the capacity of a chimney could be expressed either in terms of pounds of gases moved or discharged per second, or in terms of the horsepower equivalent of the boilers. It can be proven that the capacity of a chimney increases as the temperature of the chimney gases increases until a certain maximum chimney gas temperature is reached, after which the capacity decreases, that the temperature of the outside air and the density of the chimney gases has no appreciable effect on the capacity; that the capacity increases as the coefficient of friction decreases, but that the coefficient of friction doubtless remains constant regardless of the character of the materials of which the chimney is built, since the inside surface of nearly all chimneys is usually covered with a heavy coat of soot; that the loss of draft due to friction increases as the actual velocity of the chimney gases increases, which in turn decreases the capacity of the chimney in spite of the fact that the working velocity theoretically increases the capacity; that the capacity increases as both the height and diameter increases; and that the capacity decreases as the atmospheric pressure decreases.

In designing a new chimney, it was developed in Chapter VII that the height was equal to the required theoretical draft divided by the theoretical draft per foot of chimney, or, in other words, the sum of the various losses of draft throughout the entire installation divided by the theoretical draft per foot of chimney, both based on the same operating conditions. It was also brought out that the diameter of the chimney affected only the loss of draft due to friction and had no appreciable effect on the height over a small range of variation.

Just as the height of a chimney was determined by the amount of draft required, so is the diameter of a chimney determined by the amount of gases it is required to pass. The height of the chimney was restricted by certain working conditions, assumed or otherwise, which were imposed upon it. Likewise, the diameter is restricted by these same conditions, as well as others, the effect of which will now be discussed in detail.

Diameter Based on Pounds of Gases Passing Per Second, W_a

Assuming, in equation 164, that

$$W = W_a$$

and

$$V = V_a$$

Then

$$W_a = 33.44 \frac{A V_a W_c P_o}{T_c} \qquad 205$$

Whence

$$A = \frac{W_a T_c}{33.44 V_a W_c P_o} \qquad 206$$

and

$$D = \sqrt{\frac{W_a T_c}{26.26 W_c V_a P_o}} \qquad 207$$

$$= 0.195 \sqrt{\frac{W_a T_c}{W_c V_a P_o}} \qquad 208$$

All of the factors in equation 208 are known with the exception of V_a which, in determining the diameter, is purely a matter of choice. It is obvious that the area, and consequently the diameter, will decrease as V_a increases, and vice versa. In other words, a relatively small area, or diameter, will result when a relatively high velocity is assumed, and a relatively large area, or diameter, when a relatively low velocity is assumed.

It will be developed in a later chapter that for each different assumed value for V_a in connection with an arbitrarily selected set of operating conditions, a correspondingly different size of chimney will result. A size criterion will be established by multiplying the height by the diameter, both expressed in feet. It will be assumed that, all other conditions being equal, the relatively cheapest chimney in price will be the one whose product of diameter and height will be least. The approximate chimney gas velocity which will result in a chimney whose product of diameter and height will be least for the set of operating conditions for which the size is being determined is given by the equation:

$$V_a = \sqrt{\frac{m\ K_a\ K_D\ T_c}{0.375\ m\ \ (X_T + l) + 0.176 l + 0.284\ K_a}} \qquad 209$$

in which

$$m = \sqrt{\frac{W_a\ T_c}{26.26\ W_c\ P_o}} \qquad 210$$

$$K_a = \frac{h_F + h_B}{K_D} \qquad 211$$

$$K_D = 6.43\ P_o \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right) \qquad 212$$

$$T_c = t_c + 459.6 \qquad 213$$

X_T = number of turns or bends incidental to breeching

l = length of breeching in feet.

This equation is based on a number of qualifying factors which will be explained in a later chapter. The equation, however, is sufficiently accurate (within one-half of one per cent) for all practical purposes.

In equation 209, the value of W_a can be computed from an analysis of the fuel, the maximum rate of combustion and the area of the grates. W_c can be

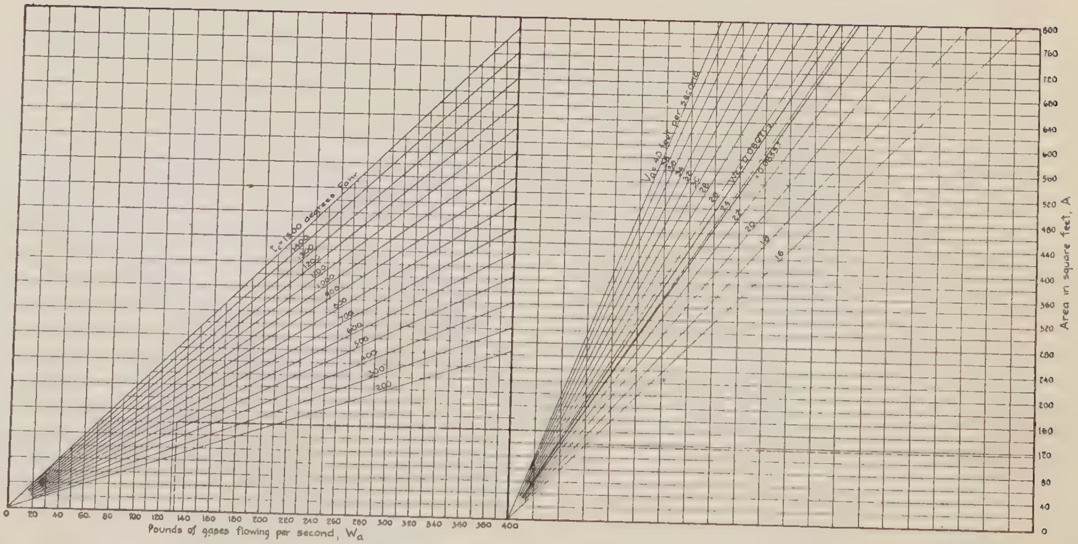

Fig. 58. Chart for determining the areas of chimneys and breechings.

Based on equation $A = \dfrac{W_a T_c}{T W_c V_a}$ Sea-level atmospheric conditions.

predicted with a fair degree of accuracy, h_F can be ascertained from Fig. 38, h_B must be obtained from the manufacturer of the boiler, X_T is known from the breeching layout, P_o depends upon the elevation of the plant, and t_o and t_c must be judiciously assumed.

Fig. 58 gives the area of the chimney for various values of W_a, T_c, W_c, and V_a.

The required diameter of a chimney may also be obtained from the equation for the capacity of a chimney. From equation 186:

$$W_a = AR_cK_{wc}K_t\sqrt{H} \tag{214}$$

in which W_a = lbs. of gases discharged or moved per second

A = area of chimney in sq. ft.

$$R_c = \frac{V_a}{V_t} = \frac{0.215\sqrt{\frac{P_o\,T_c\,h_v}{W_c}}}{8.02\sqrt{H\left(\frac{C_tT_c}{T_o}-1\right)}} \tag{215}$$

or, the ratio of the working velocity of the chimney gases to the theoretical velocity, for a circular section,

$$K_{wc} = 268.2\,W_c\,P_o \tag{216}$$

$$K_t = \sqrt{\frac{C_tT_c - T_o}{T_oT^2_c}} \tag{217}$$

and H = height of chimney in feet

Whence
$$A = \frac{W_a}{R_cK_{wc}K_t\sqrt{H}} \tag{218}$$

and
$$D = \sqrt{\frac{W_a}{0.7854R_cK_{wc}K_t\sqrt{H}}} \tag{219}$$

in which D = diameter of chimney in feet

Equation 219 is the fundamental equation for the diameter of a chimney, taking into consideration all of the observable conditions or factors as was done in the case of the required height of the chimney, and based on sea level atmospheric conditions.

This equation is much too unwieldly to handle in every-day practice and for this reason will be considerably simplified.

Therefore let $K_c = 0.7854 R_c K_{wc} K_t$ 220

Then $$D = \sqrt{\frac{W_a}{K_c \sqrt{H}}} \qquad 221$$

Equation 221 gives the diameter of a chimney in its simplest form, based on the factors used in developing the theory for the capacity of a chimney.

In order to construct a set of curves which will give the diameter of the chimney for various values of W_a, H, and K_c, it will first be necessary to determine the limits of the K_c factor.

By examples it can be shown that under average working conditions, R_c varies between 0.25 and 0.35, with an average value of 0.30. For a chimney gas density of 0.08071 lbs. per cu.ft. at 32 deg. Fahr., $K_{wc} = 3943 \times 0.08071 = 318$; and for a chimney gas density of 0.0855, $K_{wc} = 3943 \times 0.0855 = 337$. K_{wc} then varies between 318 and 337.

For a chimney gas temperature of 642 deg. Fahr., an average outside air temperature of 60 deg. Fahr., and a chimney gas density of 0.0855 lbs. per cu. ft. at 32 deg. Fahr.,

$$K_t = \sqrt{\frac{0.944 \times 1101.6 - 519.6}{519.6\ (1101.6)^2}}$$

$$= 0.000908$$

An inspection of Fig. 53 will disclose the fact that K_t varies between 0.00080 and 0.00108 for ordinary working conditions with an average of approximately 0.00090 as above noted.

From the above data, then, an average working value for K_c is equal to $0.7854 \times 0.30 \times 337 \times 0.00090 = 0.072$. For a minimum value, $K_c = 0.7854 \times 0.25 \times 318 \times 0.00080 = 0.05$; and for a maximum value, $K_c = 0.7854 \times 0.35 \times 337 \times 0.00108 = 0.10$. K_c then will vary between 0.05 and 0.10 with an average working value of 0.072. Fig. 59 gives the diameter of a chimney, D, for various values of W_a, H, and K_c. Fig. 60 gives the value of K_c.

Example: Determine the required diameter of a chimney for the following working conditions:

150 lbs. of gases moved or discharged per second,
0.0855 density of the chimney gases in lbs. per cu. ft. at 32 deg. Fahr.,
0.40 Inches of water, loss through fuel bed,
0.60 Inches of water, loss through boiler,
600 deg. Fahr., chimney gas temperature,
60 deg. Fahr., outside air temperature,
Sea level atmospheric conditions.
25 feet length of breeching,
1 turn or bend.

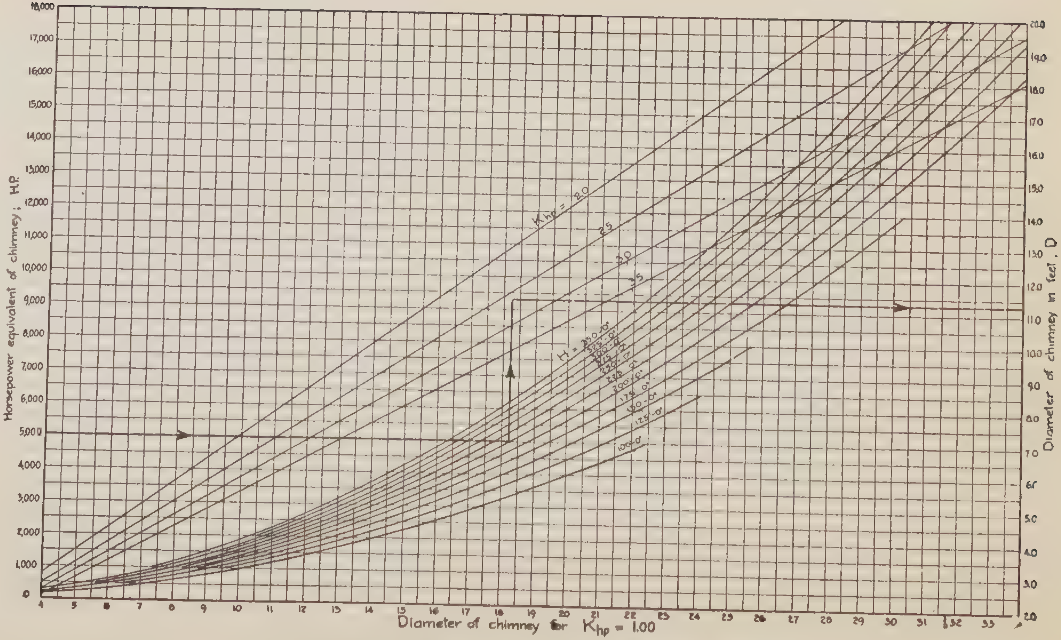

Fig. 59. Diameter of chimney for various values of W_n, K_c and H.
Based on sea level atmospheric conditions, and a circular section.

Solution

From equation 210:

$$m = \sqrt{\frac{150 \times 1059.6}{26.26 \times 0.0855 \times 14.7}} = 69.5$$

From equation 212:

$$K_D = 6.43 \times 14.7 \times \left(\frac{0.08071}{519.6} - \frac{0.0855}{1059.6}\right)$$
$$= 0.00706$$

From equation 211:

$$K_a = \frac{0.40 + 0.60}{0.00706} = 141$$

Whence from equation 209:

$$V_a = \sqrt{\frac{69.5 \times 141 \times 0.00706 \times 1959.6}{0.375 \times 69.5 \times 2 + 0.176 \times 25 + 0.284 \times 141}}$$
$$= 28.6 \text{ feet per second.}$$

and from equation 208:

$$D = 0.195 \sqrt{\frac{150 \times 1059.6}{0.0855 \times 28.6 \times 14.7}}$$
$$= 13 \text{ feet.}$$

Diameter Based on the Horsepower Equivalent of the Boilers

From equation 200:

$$\text{H.P.} = 3600 \frac{AR_cK_{wc}K_t\sqrt{H}}{W_{bh}} \qquad 222$$

Whence $$A = \frac{\text{H.P. } W_{bh}}{3600R_cK_{wc}K_t\sqrt{H}} \qquad 223$$

and $$D = \sqrt{\frac{\text{H.P. } W_{bh}}{0.7854 \times 3600R_cK_{wc}K_t\sqrt{H}}} \qquad 224$$

Let $$K_{hp} = \frac{0.7854 \times 3600 R_c K_{wc} K_t}{W_{bh}} \qquad 225$$

$$= \frac{3600 K_c}{W_{bh}} \qquad 226$$

Then $$D = \sqrt{\frac{H.P.}{K_{hp}\sqrt{H}}} \qquad 227$$

The limits for K_{hp} are found as follows: Assuming average conditions, let

$$W_{bh} = 100$$

Now for $W_c = 0.0855$ $\qquad K_{wc} = 337$

Assume $\qquad R_c = 0.30$

Also for $t_c = 600$ deg. Fahr., $T_o = 60$ deg. Fahr., and $W_c = 0.0855$,

$$K_t = 0.000906$$

Then $$K_{hp} = \frac{0.7854 \times 3600 \times 0.30 \times 337 \times 0.000906}{100}$$

$$= 2.6$$

For a minimum value, then,

$$K_{hp} = \sqrt{\frac{3600 \times 0.05}{120}}$$

$$= 1.5$$

and for a maximum value

$$K_{hp} = \frac{3600 \times 0.10}{50}$$

$$= 7.2$$

K_{hp} then will vary between 1.5 and 7.2 with an average for average operating conditions of 2.6.

Fig. 61 gives the diameter of a chimney, D, for

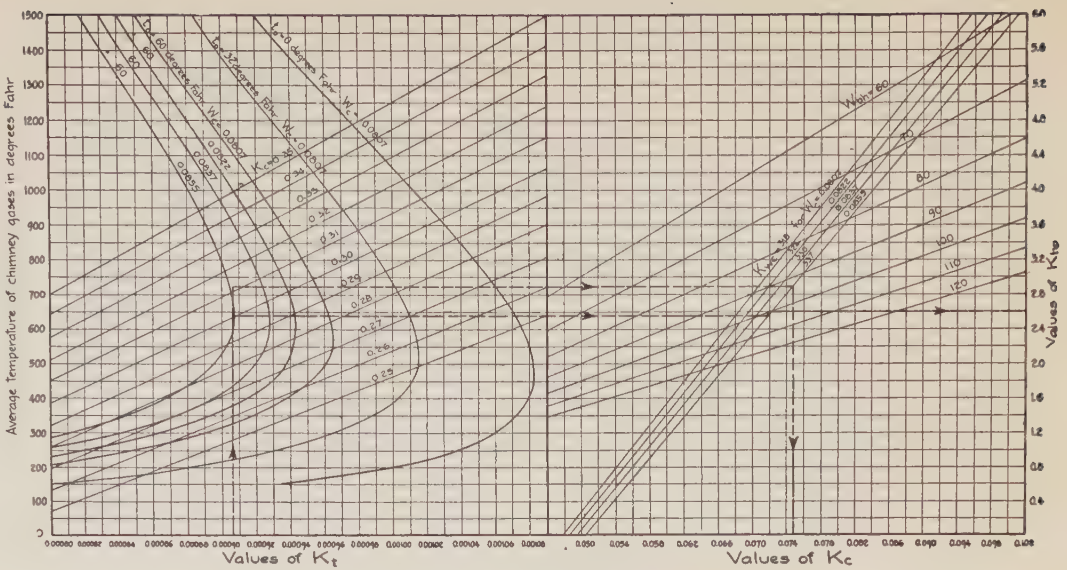

Fig. 60. Values of K_c and K_{hp} for various values of K_t R_c, K_{wc} and W_{bh}.

Based on equations $K_c = 0.7854 R_c K_{wc} K_t$ and $= \dfrac{3600 K_c}{W_{bh}} = \dfrac{2827 R_c K_{wc} K_t}{W_{bh}}$ Circular section.

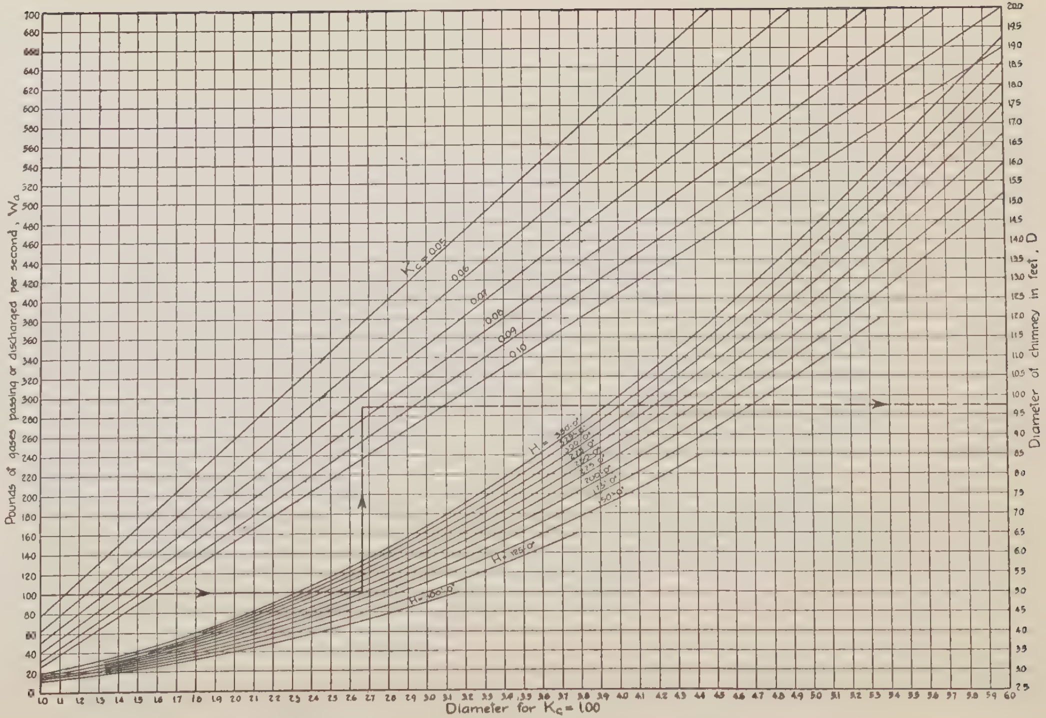

Fig. 61. Diameter of chimney for various values of H.P., K_{hp} and H.
Based on sea level atmospheric conditions, and a circular section.

various values of H.P., K_{hp}, and H. Fig. 60 gives the value of K_{hp}.

The above theory is given only as a matter of interest. It is not recommended that the diameter of a chimney be based on the horse-power equivalent of the boilers. This seems to have been the practice in the past and no doubt has led to many badly proportioned chimneys. This subject will be discussed at length in a later chapter.

Use of Charts

Figs. 59, 60, and 61 will be found of great help in determining the required diameter of a chimney. Chart 59 gives the diameter of a chimney for various values of W_a, K_c, and H; chart 61 gives the diameter for various values of H.P., K_{hp}, and H; and chart 60 gives the value of both K_c and K_{hp} for various values of K_t, R_c, K_{wc}, and W_{bh}. In Fig. 60, the values of K_t for various values of chimney gas temperatures and four values of W_c corresponding to the same four values used in the K_{wc} lines, together with an outside air temperature of 60 deg. Fahr., are also shown.

CHAPTER X

THE CHIMNEY HORSEPOWER FALLACY

In the past, several methods which have been more or less open to question, have been developed for determining the proper size of a chimney, but none has produced more unsatisfactory results, none resulted in more improper sizes, than that of determining the height and diameter of a chimney from an arbitrarily constructed table of "chimney horsepowers." In the first place there is no such term as "chimney horsepower" or "horsepower of a chimney." Such a phrase is absolutely meaningless. What is actually meant is that the chimney is to be of such a size that it will properly pass or discharge the same amount of gases that are passed to it by a boiler or set of boilers of a certain total maximum horsepower. The gases are formed in the combustion chamber, pass on through the several passes of the boiler or boilers, and are finally received by the chimney.

Manifestly it is necessary for the chimney to take care of these gases, that is to say, take them away at such a rate that space may be provided so that others can be accommodated properly, under the conditions to which the chimney itself is subjected. This rate is the same as that at which the gases are formed or generated in the combustion chamber. For example: If gases are formed in the combustion chamber at the rate of 100 lbs. per second and pass on through the boiler at this same rate, then the chimney must be of such a size that it will take away these gases from the boiler and discharge them into the upper regions at this same rate, viz: 100 lbs. per second; all under the restrictions which are arbitrarily imposed upon the chimney itself. When the diameter of a chimney is based on the same rate at which the gases are formed in the combustion chamber, there are no qualifying factors to be taken into consideration such as are necessary when the diameter is based on the horsepower equivalent. In the second place, selecting a size of chimney for a specific set of operating conditions from a table of "chimney horsepowers" is extremely dangerous practice since the height, which is dependent upon the amount of draft losses throughout the installation, may not be sufficient to create the required amount of draft to overcome these various resistances. The horsepower equivalent of a chimney does not determine the required height of a chimney. The height is determined only by the total amount of draft required.

As noted heretofore, by "horsepower equivalent" of a chimney is meant that the chimney will accommodate the gases at the same rate as a boiler, or set of boilers, of a certain boiler horsepower. The horsepower equivalent is a factor in determining the diameter of the chimney and has nothing whatever to do in determining the height.

In designing boilers, it is necessary to assume a certain rate at which the gases will be generated, speaking in terms of boiler horsepower. This rate is expressed as so many pounds of gases per boiler coal burned per boiler horsepower per hour. If C_{bh} = pounds of coal burned per boiler horespower per hour, and W_{ta} = the pounds of air required per pound of coal for complete combustion, then $W_{bh} = W_{ta} C_{bh}$ = pounds of gases per b.h.p. per hour.

Now since W_a = pounds of gases formed per second in the combustion chamber, then

$$H.P. = \frac{W_a}{\frac{W_{bh}}{3600}} = \frac{3600 W_a}{W_{bh}} \qquad 228$$

The horsepower of the boilers then is equal to 3600 times the rate per second at which the gases are generated in the combustion chamber, divided by the amount of gases formed per boiler horsepower per hour. Since these gases pass on into the chimney and must be accommodated by the latter at the same rate, the term "horsepower" is usually passed on to the chimney itself. If operating conditions were absolutely constant throughout the year and were also constant and similar for every plant regardless of size or any other condition, then a table of chimney sizes for boiler horsepowers would be of great advantage. But such is not the case; operating conditions are constantly changing. Boilers are being operated at ratings many times those of a few years ago; draft resistances or losses are much greater than formerly because of larger boilers and more complicated methods of baffling; breechings are longer; and many other changed conditions all tend to render worse than useless a table of chimney sizes based on boiler horsepowers. Most important of all is the fact that such a table of chimney sizes is necessarily based on one, and only one, set of operating conditions, and a variation in only one of the factors entering into the equation for either the height or the diameter of the chimney must of necessity change the figures in the table entirely.

It is the author's contention that the size of a chimney should never under any circumstances be based on a chimney horsepower or a boiler horsepower table. The practice is dangerous and more often than not will result in a size that is totally unfit for the conditions under which the chimney is to operate.

For the primary and only purpose of showing how a table of chimney sizes for boiler horsepowers will lead to totally unfit sizes or results, such a table will be constructed, a typical problem solved from it and then checked by comparing it with a set of actual operating conditions.

Since $$W_a = AR_cK_{wc}K_t\sqrt{H} \tag{229}$$

Then $$\text{H.P.} = \frac{3600\ AR_cK_{wc}K_t\sqrt{H}}{W_{bh}} \tag{230}$$

$$= \frac{2827\ R_cK_{wc}K_t}{W_{bh}}\ D^2\sqrt{H} \tag{231}$$

$$= K_{hp}D^2\sqrt{H} \tag{232}$$

Now for a chimney gas density of 0.0855 lbs. per cu. ft. at 32 deg. Fahr., a chimney gas temperature of 600 deg. Fahr., and an outside air temperature of 60 deg. Fahr.,

$$K_t = \sqrt{\frac{0.944 \times 1059.6 - 519.6}{519.6 \ (1059.6)^2}}$$

$$= 0.000906$$

For a chimney gas density of 0.0855 lbs. per cu. ft. at 32 deg. Fahr.

$$K_{wc} = 3943 \times 0.0855$$

$$= 337$$

For a rate of combustion of 5 lbs. of coal per b.h.p. per hour, and assuming that 20 lbs. of air per lb. of coal is required for complete combustion.

$$W_{bh} = 5 \times 20$$

$$= 100$$

Finally, assume arbitrarily

$$R_c = 0.29$$

Then assuming that the above represents a set of constants for an average set of working conditions.

$$K_{hp} = \frac{2827 \times 0.29 \times 337 \times 0.000906}{100}$$

$$= 2.5$$

Table 13, which has been constructed for illustrating various points in the text and is not offered for general use, gives the horsepower equivalent of the chimney for various heights and diameters, or the diameter and height for various boiler horsepowers or chimney horsepower equivalents, based on the value of 2.5 for K_{hp}. Fig. 62 shows the curves for these values.

It should be noted clearly that the values as

TABLE 13

Chimney Sizes for Boiler Horsepowers, or Horsepower Equivalent of Chimney

Based on equation $H.P. = 2.5D^2\sqrt{H}$

Diameter of chimney	75	100	125	150	175	200	225	250	275	300
	Horsepower of boiler, or horsepower equivalent of chimney									
3 ft. 0 in.	195	225	252	276						
3 ft. 6 in.	265	306	343	375						
4 ft. 0 in.	346	400	448	490	530					
4 ft. 6 in.	439	506	566	620	670					
5 ft. 0 in.	530	625	700	766	927					
5 ft. 6 in.		756	847	827	1000					
6 ft. 0 in.		900	1006	1102	1191	1273				
6 ft. 6 in.		1056	1181	1293	1387	1493				
7 ft. 0 in.		1225	1370	1500	1621	1732	1838			
7 ft. 6 in.		1406	1572	1722	1860	1988	2109			
8 ft. 0 in.			1789	1960	2117	2263	2400			
8 ft. 6 in.				2211	2389	2554	2709	2855		
9 ft. 0 in.				2479	2679	2864	3038	3202		
9 ft. 6 in.				2763	2984	3190	3384	3577		
10 ft. 0 in.				3062	3317	3536	3750	3953	4146	4330
10 ft. 6 in.					3646	3898	4134	4358	4570	4773
11 ft. 0 in.					4002	4278	4538	4773	5016	5239
11 ft. 6 in.					4374	4675	4959	5227	5482	5726
12 ft. 0 in.					4762	5091	5400	5692	5970	6235
12 ft. 6 in.					5167	5514	5859	6176	6477	6765
13 ft. 0 in.					5589	5975	6338	6680	7006	7318
13 ft. 6 in.					6027	6443	6834	7208	7555	7891
14 ft. 0 in.					6482	6930	7350	7747	8126	8487
14 ft. 6 in.					6953	7433	7884	8311	8716	9103
15 ft. 0 in.					7441	7955	8436	8894	9328	9743
15 ft. 6 in.						8494	9009	9496	9960	10402
16 ft. 0 in.						9051	9600	10019	10613	11085
16 ft. 6 in.						9625	10209	10761	11286	11788
17 ft. 0 in.						10218	10838	11423	11981	12514
17 ft. 6 in.						10827	11484	12105	12706	13260
18 ft. 0 in.						11455	12150	12807	13432	14029
18 ft. 6 in.						12100	12834	13528	14188	14819
19 ft. 0 in.						12763	13538	14270	14966	15631
19 ft. 6 in.						13443	14259	15030	15764	16464
20 ft. 0 in.						14142	15000	15811	16583	17320

**Do not use this table for general practice.*

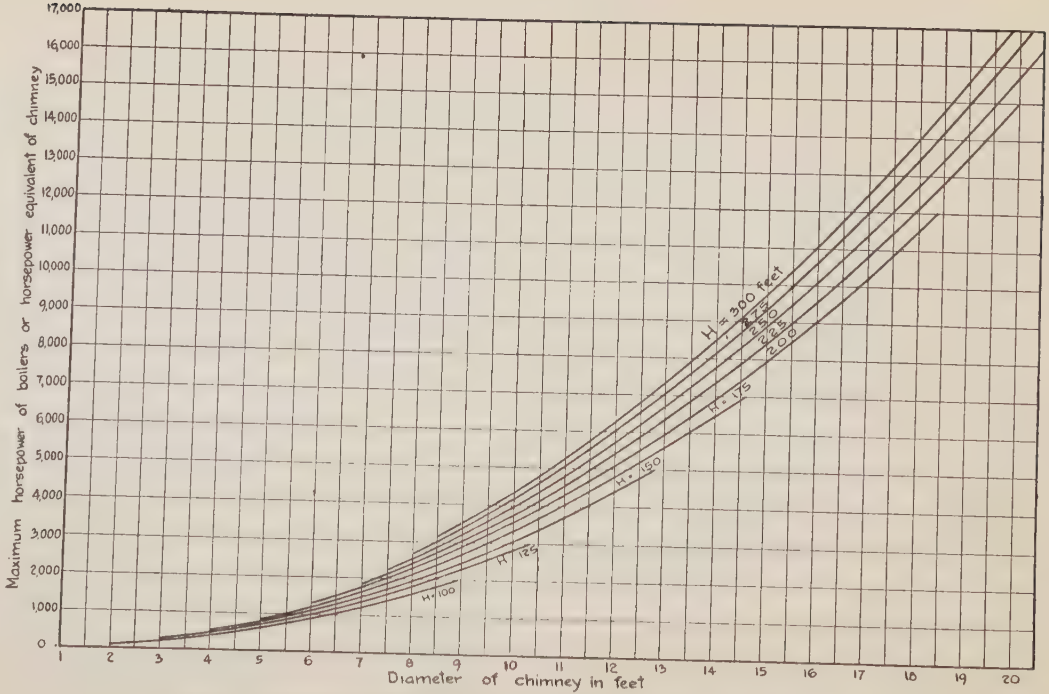

Fig. 62. Diameter of chimney for various horsepowers of boilers, or horsepower equivalents of chimneys.

Based on Equation $D = \sqrt{\dfrac{H.P.}{2.5\sqrt{H}}}$ *Note: Do not use these curves for general practice.*

given by the Table are true only for the particular set of operating conditions noted heretofore, or for any other similar set of operating conditions which will give a value of 2.5 for K_{hp}. When the value of K_{hp} is less than 2.5, then the horsepower equivalent is less than the values shown in the Table, and conversely when the value is greater than 2.5, the horsepower equivalent is greater.

An example will illustrate the above facts clearly:

A common request for a size of chimney is as follows: Give size of chimney required for two 600 h.p. boilers when run at 250 per cent rating.

The total maximum horsepower of the boilers is

$$2 \times 600 \times 2.5 = 3000 \text{ horsepower}$$

This figure is also the horsepower equivalent of the chimney.

Consulting Table 13, it will be found that the following sizes will apparently answer the purpose:

150 ft. 0 in. × 10 ft. 0 in.
175 ft. 0 in. × 9 ft. 6 in.
200 ft. 0 in. × 9 ft. 6 in.
225 ft. 0 in. × 9 ft. 0 in.
250 ft. 0 in. × 9 ft. 0 in.

Considering the lack of sufficient data, which should have been given, it is of necessity left to the judgment of the designer to select or guess at the proper size. Let it be assumed for the sake of an argument that the size of the chimney selected is 200 ft. x 9 ft. 6 in. So far, so good. Now upon further investigation, it is found that the various losses of draft are as follows:

Loss of draft through the fuel bed, = 0.40 in. of water
Loss of draft through the boiler, = 0.55 in. of water
Loss of draft through the breeching, = 0.20 in. of water
Loss of draft due to bends, = 0.15 in. of water
Total loss due to these four factors or required draft at breeching entrance of chimney = 1.30 in. of water

The losses due to friction and velocity in the chimney are of course unknown since the actual size of the chimney itself is unknown, and it is therefore necessary to assume tentative values for these two factors. Therefore assume

Loss of draft due to friction = 0.15 in. of water
Loss of draft due to velocity = 0.10 in. of water
Whence, total loss of draft (trial) = 1.55 in. of water

Let it also be assumed that the temperature of the chimney gases is equal to 550 deg. Fahr., the density of the chimney gases 0.0855 lbs. per cu. ft. at 32 deg. Fahr., and the temperature of the outside air 60 deg. Fahr. Assuming sea level atmospheric conditions, the theoretical draft per foot of chimney is equal to

$$K_D = 6.43 \times 14.7 \times \left(\frac{0.08071}{519.6} - \frac{0.0855}{1009.6}\right)$$

$$= 94.52 \times 0.0000706$$

$$= 0.00667 \text{ in. of water}$$

Whence the required height, H (trial)

$$= \frac{1.55}{0.00667} = 232 \text{ ft.}$$

Let it be assumed, for the moment, that the diameter as determined by the Table is correct, and also that the gases are formed in the combustion chamber at the rate of 85 pounds per second and pass on through the chimney at this same rate. Then, from equation 68, the loss of draft due to friction equals

$$h_f = 0.000579 \times 0.016 \times \frac{(85)^2 \times 1009.6 \times 232}{14.7 \times (9.5)^5 \times 0.0855}$$
$$= 0.16 \text{ in. of water}$$

and from equation 44 the loss due to velocity equals

$$h_v = 0.000145 \times \frac{(85)^2 \times 1009.6}{14.7 \times (9.5)^4 \times 0.0855}$$
$$= 0.10 \text{ in. of water}$$

Since these two values are practically equal to the assumed losses, the conditions of the problem are satisfied and the required height of the chimney is equal to 232 ft.

The diameter of the chimney as given by the Table will now be checked:

Now $$K_{wc} = 3943 \times 0.0855$$
$$= 337$$

And $$K_t = \sqrt{\frac{0.944 \times 1009.6 - 519.6}{519.6 \times (1009.6)^2}}$$
$$= 0.000904$$

$$R_c = \frac{0.215\sqrt{\dfrac{14.7 \times 1009.6 \times 0.10}{0.0855}}}{8.02\sqrt{232\left(\dfrac{0.944 \times 1009.6}{519.6} - 1\right)}}$$

$$= \frac{28.4}{111.5} = 0.254$$

Then $$K_C = 0.7854 \times 337 \times 0.254 \times 0.000904$$
$$= 0.0606$$

and finally $$D = \sqrt{\frac{85}{0.0606\sqrt{232}}} = 9.6 \text{ ft.}$$

or from equation 208:

$$D = 0.195 \sqrt{\frac{85 \times 1009.6}{0.0855 \times 28.4 \times 14.7}} = 9.6 \text{ ft.}$$

which checks the assumed value of the diameter taken from the Table.

Therefore, the required size of the chimney, after the true operating conditions had been determined, is found to be 232 ft. x 9 ft. 6 in. instead of 200 ft. x 9 ft. 6 in. as selected from the Table. The size of chimney selected from the tentative sizes as given by the Table happened to be a fairly judicious one. Had the 150 ft. x. 10 ft. or the 175 ft. x 9 ft. 6 in. size been selected, the height would have been entirely too short, and had the 225 ft. x 9 ft. or the 250 ft. x. 9 ft. size been selected, the diameter would have been too small.

From the above computations, it might be inferred that determining the required height and diameter of a chimney is a rather extended and long-drawnout process and that such refinement in computations, particularly in the case of the smaller sizes, is not warranted, due to the fact that there will not be much of a practical variation from that taken from a table of chimney sizes for boiler horsepowers. Such, however, is not the case. A table, such as that given on page 223, for example, seldom has any notation giving the operating conditions for which it has been constructed, other than the statement that a certain number of pounds of coal has been assumed per boiler horsepower per hour. No mention is ordinarily made of the pounds of air required per pound of coal for complete combustion, or the pounds of gases per boiler horsepower per hour, the temperature of the chimney gases, the temperature of the outside air, the density of the chimney gases, the coefficient of friction, the required draft at the breeching entrance of the chimney, the atmospheric pressure, or any other required condition. Each of the factors noted affects both the required height and diameter. If a value is assigned to each of these factors, a value computed for K_{hp}, and a table is constructed based on this particular value, the corresponding horsepower equivalents then apply only to this particular set of operating conditions. When the value of any one factor varies, the value of K_{hp} varies and the horsepower equivalent is changed as a result. It is possible for horsepower equivalents in a table to vary as much as 100 per cent from the actual figure due to a variation in the operating conditions. If a set of curves is constructed, such as those given in the previous chapter, which will take into consideration all of the factors entering into the equation for the horsepower equivalent of a chimney, then a proper size can be determined. In a table, however, such as that given by Table 13, this cannot be done even approximately.

Another equation for determining the diameter of a chimney based on the horsepower of the boilers commonly encountered is as follows:

$$D = 4.68 \ (\text{H.P.})^{2/5} \qquad 233$$

in which $D =$ diameter in inches,

or $$D = 0.39\ (\text{H.P.})^{2/5} \qquad 234$$

in which $D =$ diameter in feet.

The coefficients 4.68 and 0.39 are for an unlined steel chimney. For a brick or brick lined chimney, the coefficients usually given are 4.92 and 0.41, respectively.

Whence, from equation 234:

$$\text{H.P.} = \sqrt{\left(\frac{D}{0.39}\right)^5} \qquad 235$$

$$= 10.54 D^2 \sqrt{D} \qquad 236$$

For a coefficient of 0.41:

$$\text{H.P.} = 9.3 D^2 \sqrt{D} \qquad 237$$

An equation of this type is derived as follows: The fundamental equation for the loss of draft due to friction for a circular duct is

$$h_f = 0.000579\, f\, \frac{W^2_a\, T_c\, L}{D^5\, W_c\, P_o}$$

Then $$W^2_a = \frac{P_o\, D^5\, h_f\, W_c}{0.000579\, f\, T_c\, L} \qquad 238$$

Now since $W_a = \dfrac{\text{H.P.}\ W_{bh}}{3600}$

Then $$\left(\frac{\text{H.P.}\ W_{bh}}{3600}\right)^2 = \frac{P_o\, D^5\, h_f\, W_c}{0.000579\, f\, T_c\, L}$$

and $$\text{H.P.} = \sqrt{\frac{(3600)^2\, D^5\, h_f\, W_c\, P_o}{0.000579\, W^2_{bh}\, f\, T_c\, L}} \qquad 239$$

It is now necessary to assign numerical values to most of the factors underneath the radical sign in order to eliminate all but D. Hence assume the following values:

$h_f = 0.10$ in. of water
$W_c = 0.0855$ lbs. per cu. ft. at 32 deg. Fahr.
$W_{bh} = 120$ lbs. of gases per b.h.p. per hour
$f = 0.016$
$P_o = 14.7$ lbs. per sq. in.
$T_c = (600 + 459.6) = 1059.6$ deg. Fahr.
$L = 100$ ft.

The above figures might be said to represent an average set of working conditions commonly met with in ordinary practice. Substituting these values in equation 239 and reducing:

$$H.P. = 10.7\sqrt{D^5} \qquad 240$$

Fig. 63 gives the value of H.P. for various values of D as computed from equation 234.

The method of determining the diameter of a chimney from the horsepower of the boilers, or the horsepower equivalent of the chimney, as given by equations 236, 237 and 240, is subject to even greater criticism than that given by equation 232. Each of the seven factors to which values have been assigned will vary greatly as working conditions change, and as a consequence the horsepower equivalent of the chimney will vary greatly.

For example, h_f may vary from 0.04 to as much as 0.30 in. of water; W_c, from 0.08071 to 0.0855 lbs. per cu. ft. at 32 deg. Fahr., or greater; W_{bh}, from 50 to 120 lbs. of gases per b.h.p. per hour; P_o, from 12.5 or less to 14.7 lbs. per sq. in.; T_c,

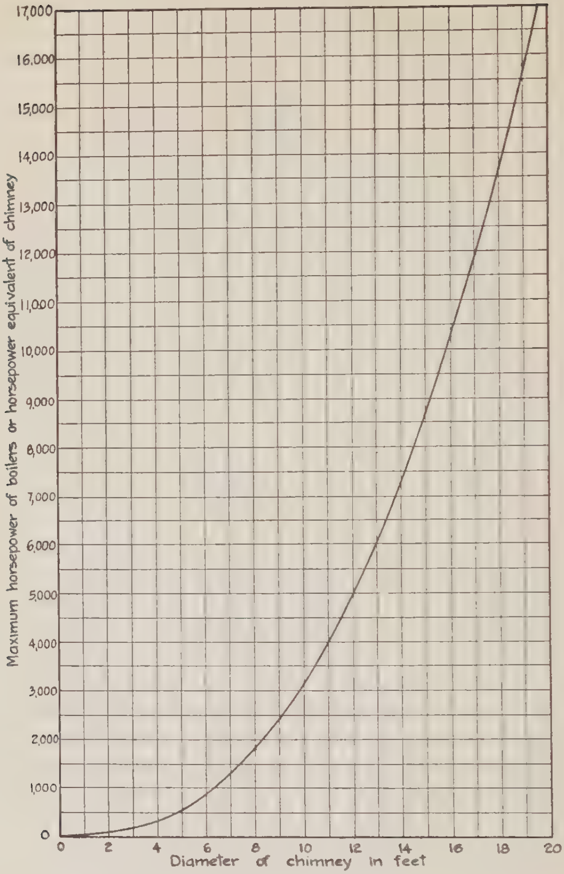

Fig. 63. Diameter of Chimney for Various Horespowers of Boilers, or Horsepower Equivalents of Chimneys. Based on Equation $D = 0.39 \sqrt[5]{(H.P.)^2}$

Note: Do not use this curve for general practice.

from a figure as low as 809.6 (350 + 459.6) to 1459.6 (1000 + 459.6), or greater; and L, from 75 to 350 ft., or even higher. If h_f is equal to 0.20 in. of water, as is often the case with a tall chimney, and the rest of the assumptions remain constant, then the coefficient before the radical sign in equation 240 will equal 15.2. If W_c is equal to 0.08071, the coefficient will equal 10.4. If W_{bh} is equal to 100, the coefficient will equal 12.9. If W_{bh} is equal to 80, the coefficient will equal 16.4. If P_o is equal to 13.5, the coefficient will equal 11.2. If T_c is equal to 859.6 (400 + 459.6), the coefficient will equal 11.9. If T_c is equal to 1259.6 (800 + 459.6), the coefficient will equal 9.8. If L is equal to 200, the coefficient will equal 7.6. If L is equal to 350, the coefficient will equal 5.7.

Countless combinations could be given whereby this coefficient would vary as much as fifty per cent from that given in equations 236, 237 and 240. Sufficient have been given, however, to show that determining the diameter, or horsepower equivalent of a chimney by this type of equation gives results that may be worse than pure guesses. As a matter of fact, in extreme cases, not even approximate results are obtained.

Several other formulas or equations are in existance for determining the diameter, or horsepower equivalent, of a chimney which contain a coefficient that is as variable as the weather but concerning which nothing whatsoever is mentioned, leaving only the impression that the equation is a hard and fast one from which reliable results may be obtained at all times regardless of the conditions under which the plant is operating.

Again let it be stated with great emphasis that the required height of a chimney can be determined only from the amount of required draft and the diameter only from the amount of gases generated in the combustion chamber, and under no conditions should either the diameter or the height be based on the horsepower of the boilers.

CHAPTER XI

ALTITUDE AND ITS EFFECT

In the derivation of the equations made heretofore for the draft and capacity, and also the height and diameter, of a chimney, it has been assumed that the chimney itself is located at sea level and consequently is under what is usually termed standard, or sea level, atmospheric conditions. The atmospheric pressure at sea level is equal to 14.7 lbs. per sq.in., or 2116.8 lbs. per sq. ft. This value expressed in barometric pressure is equal to 29.92, or practically 30.00 in. of mercury. Normally, pressures above that noted would indicate that the location of the chimney is below sea level, and pressures below this figure would indicate that the chimney is at an elevation. Local weather conditions, however, often affect the atmospheric pressure for a relatively short period of time, but such variations may be disregarded entirely since they have only a temporary effect on the performance of a chimney. In this text it has been assumed that the normal barometric pressure at sea level is equal to 29.92 in. of mercury and that all elevations have a normal barometric pressure as given by the equation noted below, the effect of the variations due to the weather being disregarded entirely.

There is a definite and constant relation between altitude and atmospheric pressure expressed in pounds per square inch, or barometric pressure expressed in inches of mercury. This relation is expressed by the equation

$$E_1 = 62{,}737 \log. \frac{29.92}{B_o} \qquad 241$$

in which E_1 = altitude above sea level in feet

B_o = observed barometric pressure in inches of mercury

This equation is based on a mean outside air temperature of 50 deg. Fahr., but no allowance made for humidity.

Since the normal atmospheric pressure at sea level is equal to 14.7 lbs. per sq.in., or 29.92 in. of mercury, then

$$P_o = 0.491B_o \qquad 242$$

and $$B_o = 2.035P_o \qquad 243$$

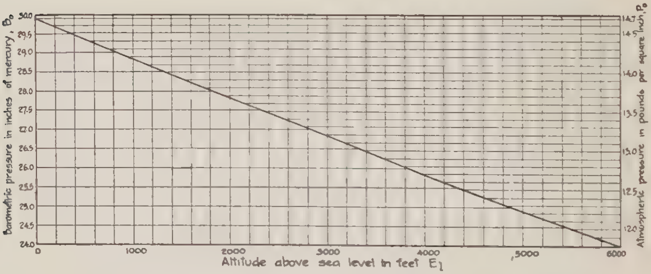

Fig. 64. Relation of barometric pressure and atmospheric pressure to altitude.

Based on equation $E_1 = 62{,}737 \log. \frac{29.92}{B_o}$

TABLE 14

ALTITUDES FOR VARIOUS ATMOSPHERIC AND BAROMETRIC PRESSURES

Based on equation $E_1 = 62{,}737 \log. \frac{29.92}{B_o}$

B_o	P_o	E_1	B_o	P_o	E_1
29.92	14.70	0	27.0	13.26	2797
29.9	14.69	18	26.9	13.22	2898
29.8	14.64	109	26.8	13.17	3000
29.7	14.60	201	26.7	13.12	3102
29.6	14.55	293	26.6	13.07	3204
29.5	14.50	385	26.5	13.02	3306
29.4	14.45	478	26.4	12.97	3409
29.3	14.40	572	26.3	12.92	3513
29.2	14.35	665	26.2	12.87	3618
29.1	14.30	758	26.1	12.82	3723
29.0	14.25	851	26.0	12.78	3828
28.9	14.20	944	25.9	12.73	3932
28.8	14.15	1038	25.8	12.68	4037
28.7	14.10	1133	25.7	12.63	4143
28.6	14.05	1228	25.6	12.58	4249
28.5	14.00	1324	25.5	12.53	4355
28.4	13.96	1420	25.4	12.48	4462
28.3	13.91	1516	25.3	12.43	4570
28.2	13.86	1612	25.2	12.38	4678
28.1	13.81	1709	25.1	12.33	4786
28.0	13.76	1806	25.0	12.28	4894
27.9	13.71	1903	24.9	12.23	5003
27.8	13.06	2001	24.8	12.18	5113
27.7	13.61	2099	24.7	12.13	5223
27.6	13.56	2198	24.6	12.09	5334
27.5	13.51	2297	24.5	12.04	5445
27.4	13.46	2397	24.4	11.99	5557
27.3	13.41	2497	24.3	11.94	5669
27.2	13.36	2597	24.2	11.89	5780
27.1	13.31	2697	24.1	11.84	5894
			24.0	11.79	6008

Table 14 gives the altitude for various barometric pressures expressed in inches of mercury, together with the corresponding pressures expressed in pounds per square inch. Fig. 64 shows the general relation between altitude and pressure.

It will be seen that the altitude does not vary directly as the atmospheric pressure. The curve representing this variation is slightly concave downward. This is due to the fact that the altitude varies as the logarithm of a ratio and therefore cannot be expressed as a straight line when plotted on the ordinary co-ordinates. The deviation from a straight line, however, is very slight.

Table 15 gives the approximate elevations above sea level of various cities throughout the United States. These elevations were taken from various pamphlets which were issued by The U. S. Weather Bureau to which due credit should be given for this very important information. This table will be found to be of immense value in determining whether an elevation has an appreciable effect on the size or performance of a chimney.

Effect of Altitude, or a Variation in Atmospheric Pressure, on Draft

In the case of draft, the density of the outside air decreases as the altitude increases and consequently the difference in pressure decreases, provided the density of the chimney gases does not undergo a change. If the density of the chimney gases also decreases, there will still be a variation in the difference in pressure, but the relative difference will not be as great. In any case, then, the draft of a chimney decreases as the altitude of the plant increases and as the barometric or atmospheric pressure decreases. In the derivation of the

APPROXIMATE ELEVATION OF CITIES ABOVE SEA LEVEL

City	*Elev.*	*City*	*Elev.*
Abilene, Tex.	1750	Little Rock, Ark.	300
Amarillo, Tex.	3690	Los Angeles, Cal.	330
Asheville, N. C.	2250	Louisville, Ky.	460
Atlanta, Ga.	1130	Madison, Wis.	955
Atlantic City, N. J.	55	Memphis, Tenn.	400
Baker City, Ore.	3430	Mobile, Ala.	55
Bismarck, N. Dak.	1680	Montgomery, Ala.	220
Boise, Idaho	3270	Moorhead, Minn.	935
Boston, Mass.	125	Nashville, Tenn.	545
Brownsville, Tex.	35	New Orleans, La.	55
Buffalo, N. Y.	690	New York City, N. Y.	315
Cairo, Ill.	360	Norfolk, Va.	55
Charles City, Iowa	1005	Northfield, Vt.	870
Charleston, S. C.	50	North Platte, Neb.	2825
Chattanooga, Tenn.	760	Oklahoma City, Okla.	1240
Cheyenne, Wyo.	6105	Omaha, Neb.	1125
Chicago, Ill.	825	Palestine, Tex.	510
Cincinnati, Ohio	630	Parkersburg, W. Va.	640
Cleveland, Ohio	740	Peoria, Ill.	520
Columbia, Mo.	785	Philadelphia, Penn.	120
Columbus, Ohio	825	Phoenix, Ariz.	1105
Concordia, Kan.	1410	Pittsburgh, Penn.	840
Corpus Christi, Tex.	20	Pocatello, Idaho	4470
Dallas, Tex.	460	Portland, Ore.	10
Davenport, Iowa	615	Pueblo, Colo.	4735
Del Rio, Tex.	950	Raleigh, N. C.	390
Denver, Colo.	5310	Rapid City, S. Dak.	3260
Des Moines, Iowa	870	Red Bluff, Cal.	335
Detroit, Mich.	725	Roseburg, Ore.	525
Devils Lake, N. Dak.	1430	Roswell, N. Mex.	3570
Dodge City, Kan.	2505	St. Joseph, Mo.	850
Dubuque, Iowa	700	St. Paul, Minn.	850
Duluth, Minn.	700	St. Louis, Mo.	570
Eastport, Maine	55	Salt Lake City, Utah	4345
El Paso, Tex.	3770	San Antonio, Tex.	705
Eureka, Cal.	65	San Diego, Cal.	70
Evansville, Ind.	385	San Francisco, Cal.	155
Flagstaff, Ariz.	6885	Santa Fe, N. Mex.	7000
Fort Smith, Ark.	480	Sault Ste. Marie, Mich.	640
Fort Wayne, Ind.	790	Seattle, Wash.	120
Fresno, Cal.	330	Sheridan, Wyo.	3740
Galveston, Tex.	40	Shreveport, La.	250
Goodland, Kan.	3690	Sioux City, Iowa	1165
Grand Junction, Colo.	4595	Spokane, Wash.	1945
Grand Rapids, Mich.	645	Springfield, Ill.	645
Green Bay, Wis.	615	Springfield, Mo.	1325
Harrisburg, Penn.	380	Tampa, Fla.	35
Hatteras, N. C.	10	Tatoosh Island, Wash.	85
Havre, Mont.	2480	Terre Haute, Ind.	485
Helena, Mont.	4110	Toledo, Ohio	675
Huron, S. Dak.	1310	Valentine, Neb.	2595
Indianapolis, Ind.	765	Vicksburg, Miss.	95
Jacksonville, Fla.	45	Washington, D. C.	110
Kalispell, Mont.	2945	Wichita, Kan.	1350
Kansas City, Mo.	965	Williston, N. Dak.	1875
Keokuk, Iowa	615	Winnemucca, Nev.	4340
Knoxville, Tenn.	545	Wytheville, Va.	2370
Lander, Wyo.	5380	Yellowstone, Wyo.	7740
Lexington, Ky.	990	Yuma, Ariz.	140

equation for the draft of a chimney, it was assumed that the density of both the outside air and the chimney gases varied directly as the change in atmospheric pressure. Hence the draft will vary directly as the atmospheric pressure, but not directly as the altitude. The theoretical draft of a chimney is given by the equation:

$$D_t = 0.1923HT\ \frac{P_o}{P}\left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right) \qquad 244$$

$$= \frac{P_o}{P}\left[0.1923HT\left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right)\right] \qquad 245$$

or

$$D_t = \frac{B_o}{B}\left[0.1923HT\left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right)\right] \qquad 246$$

Let

$$\frac{P_o}{P} = \frac{B_o}{B} = R_a \qquad 247$$

Then

$$D_{tx} = D_t\ \frac{P_o}{P} = D_t\ \frac{B_o}{B} = D_t R_a \qquad 248$$

in which D_{tx} = theoretical draft at the altitude corresponding to an atmospheric pressure of P_o, or a barometric pressure of B_o.

The available draft of a chimney is given by the equation:

$$D_a = D_t - (h_f + h_v)$$

$$= 0.1923HT\ \frac{P_o}{P}\ \left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right) - \left(0.1923\ W_c\ \frac{P_o}{P}\ \frac{T}{T_c}\ \frac{V_a^2}{2g}\right.$$

$$0.1923\ f\ W_c\ \frac{P_o}{P}\ \frac{T}{T_c}\ \frac{V_a^2}{2g}\ \frac{L}{C_d} \qquad 249$$

$$= D_t\ \frac{P_o}{P} - \left(h_f\ \frac{P_o}{P} + h_v\ \frac{P_o}{P}\right) \qquad 250$$

$$= \frac{P_o}{P}\left[D_t - (h_f + h_v)\right. \qquad 251$$

$$= \frac{B_o}{B}\left[D_t - (h_f + h_v)\right] \qquad 252$$

Then, as before,

$$D_{ax} = D_a \frac{P_o}{P} = D_a \frac{B_o}{B} = D_a R_a \qquad 253$$

in which D_{ax} = available draft at the altitude corresponding to an atmospheric pressure of P_o, or a barometric pressure of B_o

The draft, theoretical and available, of a chimney varies directly as the ratio of the atmospheric or barometric pressure at altitude to that at sea level. Fig. 65 gives the ratio or correction factor for the theoretical and available draft of a chimney for the altitudes and pressures as noted.

Example

If the theoretical draft of a chimney 140 ft. high designed for sea level atmospheric conditions is equal to 1.00 in. of water, what will be the intensity of the draft of this same chimney at an altitude or elevation of 766 ft. above sea level?

Solution

From Table 14, the barometric pressure corresponding to an elevation of 766 ft. above sea level is equal to approximately 29.1 in. of mercury. Whence the corrected draft is equal to

$$1.00 \times \frac{29.10}{29.92} = 0.973 \text{ in. of water}$$

Or, from Fig. 65, the ratio or correction factor for an elevation of approximately 800 feet above sea level is equal to 0.97. Whence

$$D_{tx} = 1.00 \times 0.97 = 0.97 \text{ inches of water}$$

Effect of Altitude, or a Variation in Atmospheric Pressure, on the Height of a Chimney

Since the draft of a chimney decreases as the altitude increases and as the atmospheric pressure decreases, it follows that the height of a chimney must be increased in order that the required amount of draft may still be maintained. The required height of a chimney is given by the equation:

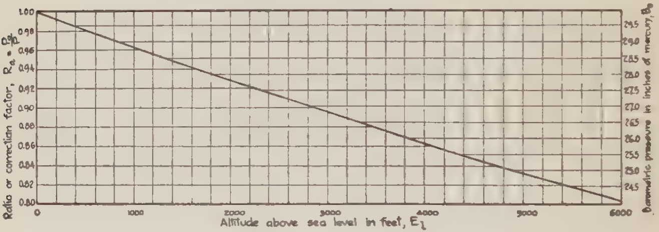

Fig. 65. Ratio or correction factor for draft for variation in atmospheric pressure.

$$H = \frac{D_t}{\frac{P_o}{P}\left[0.1923T\left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right)\right]} \qquad 254$$

$$= \frac{D_t}{\frac{P_o}{P}K_D} \qquad 255$$

Then $$H_x = \frac{P}{P_o}\frac{D_t}{K_D} = \frac{B}{B_o}\frac{D_t}{K_D} = \frac{1}{R_a}\frac{D_t}{K_D} = \frac{1}{R_a}\,H \qquad 256$$

in which H_x = required height of chimney at the altitude corresponding to an atmospheric pressure of P_o, or a barometric pressure of B_o

The required height of a chimney then varies inversely as the ratio of the atmospheric pressure at altitude to that at sea level.

Fig. 66 gives the ratio or correction factor for the required height of a chimney for the altitudes and atmospheric pressures noted.

Example

A chimney 150 ft. high designed for sea-level atmospheric conditions creates a theoretical draft of 1.059 in. of water under certain specific conditions. What will be the required height of chimney to produce the same amount of draft at an altitude of 765 ft. above sea level?

Solution

From Table 14, the barometric pressure corresponding to an elevation of 765 ft. is equal to approximately 29.1 in. of mercury. Whence:

$$H_x = \frac{29.92}{29.1} \times 150 = 1.028 \times 150 = 154.2 \text{ ft.}$$

Or, from Fig. 66, the ratio factor for an elevation of approximately 800 feet is equal to 1.03. Whence:

$$H_x = 150 \times 1.03 = 154.5 \text{ ft.}$$

In the above analysis, it has been assumed that the draft is constant for a given rate of combustion and for a given rate of operation of the boilers, and that a change in altitude has no effect other than a change in the density of both the outside air and the chimney gases. It will be noted that a variation in the altitude has an appreciable effect on the required height of a chimney even for elevations as low as 500 ft. above sea level. The increase in height amounts to about 4 per cent for an elevation of 1000 ft., 8 per cent for an elevation of 2000 ft., 12 per cent for an elevation of 3000 ft., and so on, or an average of about 4 per cent per 1000 ft. increase in altitude.

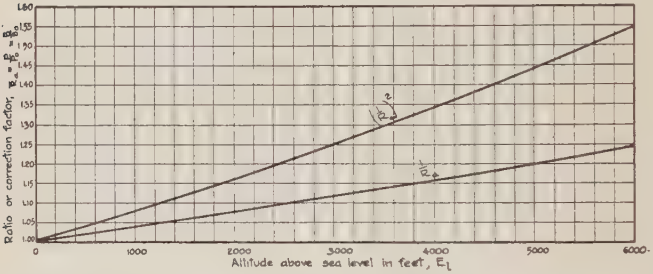

Fig. 66. Ratio or correction factor for height of chimney for variation in atmospheric pressure.

Effect of Altitude, or a Variation in the Atmospheric Pressure, on the Capacity of a Chimney

The theory for the capacity of a chimney was developed under the assumption that the plant was operating at sea level and consequently under sea level atmospheric conditions. Since a variation in the elevation or atmospheric pressure affects the draft of a chimney, it follows that the capacity also will be affected. The general equation for the capacity of a chimney may be written:

$$W_a = \frac{P_o}{P} \frac{A\,T\,W_c\,R_c\,V_t}{T_c} \qquad 257$$

It is evident that a variation in the atmospheric pressure cannot affect the factors A, T, W_c or T_c. Therefore only the factors R_c and V_t will be subjected to a change.

Now $R_cV_t = V_a$ 258

From equation 27, it will be seen that V_a varies as the expression

$$\sqrt{\frac{P}{P_o}} \qquad 259$$

or, in other words, the actual or working velocity of the chimney gases varies as the square root of the ratio of the atmospheric pressure at sea level to that at altitude. Since the velocity of the chimney gases increases as the atmospheric pressure decreases and the altitude increases, it follows that the capacity of a chimney must also increase in this same manner. This fact becomes more apparent when it is recalled that, since the density of the outside air and the chimney gases decreases as the altitude increases, more air must be supplied at altitude than at sea level in order that complete combustion of the fuel will be effected. In order to secure more air for combustion, the velocity must be correspondingly increased which in turn involves modification in furnace and boiler design, factors which are not within the province of this work.

However, it is not advantageous to have the velocity of the chimney gases increase unnecessarily, or even at all, and therefore it is assumed that the velocity of the chimney gases remains constant regardless of the altitude. In order to assure this condition, it is necessary to modify the diameter of the chimney.

Effect of Altitude, or a Variation in the Atmospheric Pressure on the Diameter of the Chimney

As stated above, in the case of the capacity of a chimney, a constant weight of air is required to develop a required horsepower equivalent; and since the density of the outside air decreases as the altitude increases, the velocity of the incoming air must be correspondingly greater at an altitude than at sea level in order to supply the proper amount of air for complete combustion. This results in increased velocities throughout the entire installation. This velocity is inversely proportional to the barometric pressure and the velocity head inversely proportional to the square of the barometric pressure. This increased velocity results in increased losses due to friction. This frictional loss may be compensated by increasing the diameter of the chimney so that the frictional loss will be the same as at sea level. It is ordinarily assumed that the increase in the diameter will be equal inversely to the two-fifths power of the ratio of the barometric pressure at altitude to that as sea level. Whence:

$$D_x = D \left(\frac{P}{P_o}\right)^{\frac{2}{5}} = D \left(\frac{1}{R_a}\right)^{\frac{2}{5}} \qquad 260$$

in which D_x = diameter of chimney at the altitude corresponding to an atmospheric pressure of P_o or a barometric pressure of B_o.

Fig. 67 gives the ratio or correction factor for the diameter of a chimney for the altitude and barometric pressures as noted. It will be seen that the diameter of a chimney is affected much less than the height by a change in altitude. The average increase in the diameter amounts to about one-tenth of one per cent per 1000 ft. increase in altitude. The effect, of course, is more noticeable in chimneys with large diameters than in those with small diameters.

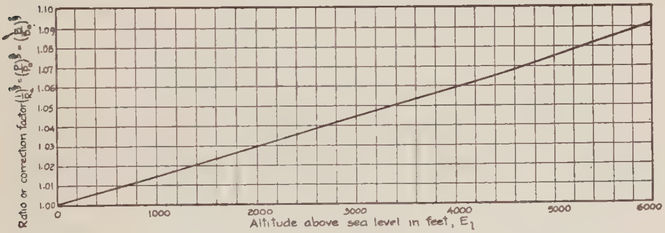

Fig. 67. Ratio or correction factor for diameter of chimney for variation in atmospheric pressure.

In increasing the diameter by the two-fifths power of the ratio of the barometric pressure at sea level to that at altitude, it is evident that the height of the chimney should be increased by the square of this ratio. In designing boilers for high altitudes, however, the assumption is usually made that a given grade of fuel will require the same draft in inches of water at the damper side of the chimney as at sea level, and as a consequence the height of the chimney will vary directly as the ratio of the barometric pressure at sea level to that at altitude. Also repeated tests have shown that there is practically no difference in the combustion rates for coal at high altitudes, providing the intensity of the draft is the same, and as a result the height will again vary directly as the ratio noted. The true value of the variation in the height of the chimney lies between the direct ratio and the square of the ratio. If the assumption be made that the true value lies midway between the direct ratio and the square of the ratio, no appreciable difference will be noted in the increased height below an altitude of 5000 ft. See Fig. 66. Above 5000 ft., however, the square of the ratio increases fast and at an elevation of 10,000 ft., the square of the ratio is 50 per cent greater than the direct ratio, or 25 per cent greater than the average between the two. Since the altitude of practically all the plants built in this country is well below 5000 ft., ample accuracy will be obtained by assuming that the height of a chimney in all cases varies directly as the ratio of the barometric pressure at sea level to that at altitude, or inversely as the ratio of the barometric pressure at altitude to that at sea level.

It should be noted in particular that the increase in the diameter due to altitude is made to maintain the same friction loss and that the increase in altitude has no effect directly on the capacity. The increase in the diameter as the two-fifths power of the ratio is a correction to an element of draft and not to the capacity.

For extremely high altitudes, the increase in the height of the chimney may make the proportion of height to diameter very impracticable. In this case, it is customary to increase the grate surface of the boilers which in turn reduces the combustion rate, and thereby reduces the draft required through the fuel bed.

In determining the height and diameter of a chimney at an altitude, the correction for altitude should be applied to the final result as determined from the elementary equations and not to each separate factor entering into the equations.

Since the changes in the height and diameter of a chimney at an altitude are due to a variation in the atmospheric or barometric pressure, it follows that variations in the barometric pressure due to causes other than a change in altitude, such as variations due to weather changes, will have a similar effect on the size, or the performance. Upon the approach of a storm, the barometric pressure usually falls and in this case the draft becomes less and the effective height of an existing chimney is shortened. Likewise the effective diameter will become less due to the increased velocity of the chimney gases.

Example

The diameter of a chimney for a certain set of operating conditions, based on sea level atmospheric conditions, is 10.00 ft. What will be the required diameter at an elevation of 1500 ft.?

Solution

From Table 14, the barometric pressure corresponding to an elevation of 1500 ft. is approximately 28.3 in. of mercury. Whence:

$$D_x = 10.00 \times \left(\frac{29.92}{28.30}\right)^{\frac{2}{5}} = 10.00 \times 1.022 = 10.22 \text{ ft.}$$

Or, from Fig. 67, the ratio or correction factor for an elevation of 1500 ft. is equal to 1.022. Whence:

$$D_x = 10.0 \times 1.022 = 10.22 \text{ ft.}$$

An extended discussion of the effect on the loss of draft due to friction of a variation in the diameter of the chimney was given in Chapter III.

Summary

In designing a new chimney for an altitude, the procedure is to design the structure for sea level atmospheric conditions and then correct the height by multiplying the latter by the ratio of the atmospheric pressure at sea level to that at altitude, and the diameter by multiplying by the two-fifths power of the ratio of the atmospheric pressure at sea level to that at altitude. The two-fifths power of the ratio is best worked out with the aid of logarithms as follows: Find the log of the ratio from a log table. Multiply this log by 2 and then divide this product by 5. The number corresponding to this log quotient is the required ratio or correction factor.

For some unaccountable reason, the size of a required chimney is seldom corrected for altitude. It has been the usual custom to determine both the height and the diameter for sea level atmospheric conditions and then use this size regardless of the altitude of the plant. If, for example, a certain set of operating conditions require a chimney 200 ft. in height and 10.00 ft. in diameter at sea level, the height will be increased to

$$\frac{29.92}{29.10} \times 200 = 1.03 \times 200 = 206 \text{ ft.}$$

and the diameter to

$$\frac{29.92}{29.10}\Big)^{\frac{2}{5}} \times 10.00 = 1.012 \times 10.00 = 10.12 \text{ ft.}$$

at an elevation of approximately 760 ft. This includes such cities as Indianapolis, Detroit, Chicago, Cleveland, Cincinnati, and others. For an elevation of approximately 1500 ft. which includes such cities as Bismark, N. Dak., Concordia, Kan., Spokane, Wash., Phoenix, Ariz., and others, the height will be increased to

$$\frac{29.92}{28.30} \times 200 = 1.05 \times 200 = 210 \text{ ft.}$$

and the diameter to

$$\left(\frac{29.92}{28.30}\right)^{\frac{2}{5}} \times 10.00 = 1.02 \times 10.00 = 10.20 \text{ ft.}$$

For an elevation of 3700 ft. which includes such cities as Amarillo, Tex., El Paso, Tex., Goodland, Kan., Roswell, New Mex., Sheridan, Wyo., and others, the height will be increased to

$$\frac{29.92}{26.10} \times 200 = 1.146 \times 200 = 229.2 \text{ ft.}$$

and the diameter to

$$\left(\frac{29.92}{26.10}\right)^{\frac{2}{5}} \times 10.00 = 1.056 \times 10.00 = 10.56 \text{ ft.}$$

At Denver, Colo., and Leander, Wyo., where the elevation is approximately 5300 ft., the height will be increased to

$$\frac{29.92}{24.60} \times 200 = 1.216 \times 200 = 243.2 \text{ ft.}$$

and the diameter to

$$\left(\frac{29.92}{24.60}\right)^{\frac{2}{5}} \times 10.00 = 1.082 \times 10.00 = 10.82 \text{ ft.}$$

From these few examples, it will be seen that the elevation of the plant has a tremendous effect on the required height, and a material effect on the diameter of a chimney.

CHAPTER XII

CHIMNEY PERFORMANCE

In dealing with a problem involving a chimney, it is necessary at the outset to differentiate between two possible purposes in view. That is to say, is a new chimney to be so designed or proportioned that certain presupposed operating conditions will be satisfied; or is the performance of an existing or working chimney to be investigated. The theory both for determining the size of a new chimney and investigating the performance of an old or a working chimney is more or less correlated, and the subject matter in the previous chapters has been developed on this basis. In the first case, the size of the chimney itself is unknown and it is therefore necessary to use the cut-and-try process until all of the conditions involved in the operation are satisfied, while in the second case the actual height and diameter are known and the operating conditions as they exist are applied to the structure and its behavior examined while operating under these conditions.

In investigating the performance of a chimney, it is necessary to have the following data and information:

1. Height of chimney
2. Diameter of chimney
3. Temperature of the chimney gases

4. Density of the chimney gases
5. Temperature of the outside air
6. Atmospheric pressure, or altitude of plant

In addition to the above major factors, the following conditions should be known:

1. Material used in construction of chimney, that is steel, brick, or reinforced concrete
2. Character of inside surface of chimney
3. Physical condition of chimney, that is, is it air-tight or does it show cracks
4. Height and thickness of lining
5. Is there an air-space between shaft and lining
6. Number, location, size, and orientation of breeching openings
7. Type of construction around top of chimney
8. Location with respect to buildings, bluffs, valleys, etc.
9. Presence of soot collectors, spark arresters, baffle wall, etc., inside of chimney
10. Does breeching fit opening tight or not

All of these factors appertain to the chimney alone and may affect both the draft and the capacity in one way or another.

The following information is required on the boilers, fuel and breeching:

Boilers:
1. Size
2. Make
3. Normal rated horsepower
4. Maximum rating
5. Area of grates

Fuel:
1. Kind
2. Character and condition

3. Amount burned per square foot of grate surface per hour, or rate of combustion
4. Analysis
5. Amount of air required for complete combustion

Breeching:
1. Length
2. Size and shape
3. Character of inside surface
4. Number of bends or turns

With all of the above information at hand, the performance of a working chimney can be completely investigated and analyzed.

In computing the size of a new chimney, both the height and diameter are made sufficiently large so that all maximum operating conditions will be amply taken care of, even if all of these conditions should be at a maximum at the same time. When all of the operating conditions are at a maximum, the chimney is said to be working at actual capacity, unless some allowance has been made for future expansion. When any operating condition becomes greater than that originally assumed, the chimney is said to be overloaded, or is being worked above capacity. On the other hand, when any condition becomes less than that originally assumed, the chimney is working at less than actual capacity. The latter is almost universally true, since it is rarely the case that a properly designed chimney will be working at even actual capacity. Oftentimes a chimney is designed with respect to future requirements, and in this case it is evident that the structure is ordinarily working far below capacity.

In order to show how a variation in the operating conditions of a plant and chimney affect the performance of the chimney itself, a typical set of average operating conditions for which the structure was originally designed will be assumed, and each variable factor will be made to vary from a maximum to a minimum value while the rest of the conditions remain constant and unchanged. The following conditions will be assumed:

200	ft., height of chimney
10	ft., diameter of chimney
600	deg. F., temperature of chimney gases
0.0855	density of the chimney gases in pounds per cu.ft. at 32 deg. F.
60	deg. F., temperature of the outside air
14.7	lbs. per sq.in., or
29.92	in. of mercury, atmospheric pressure (sea level atmospheric conditions)

Theoretical Draft

The theoretical draft of a chimney 200 ft. in height for the conditions noted above is equal to:

$$
\begin{aligned}
D_t &= 6.43 \times 200 \times 14.7 \times \left(\frac{0.08071}{519.6} - \frac{0.0855}{1059.6}\right) \\
&= 1.412 \text{ in. of water}
\end{aligned}
$$

This intensity of theoretical draft is a quantity which cannot be accurately observed by a draft gauge. If, however, the gases within the chimney be absolutely motionless, and there be no leakage, the observed draft at any point of the chimney will be approximately the same as the computed value.

The theoretical draft is the starting point of all draft problems and represents the maximum intensity of difference in pressure which is available to overcome all of the losses of draft or pressure drops throughout the entire installation. In the

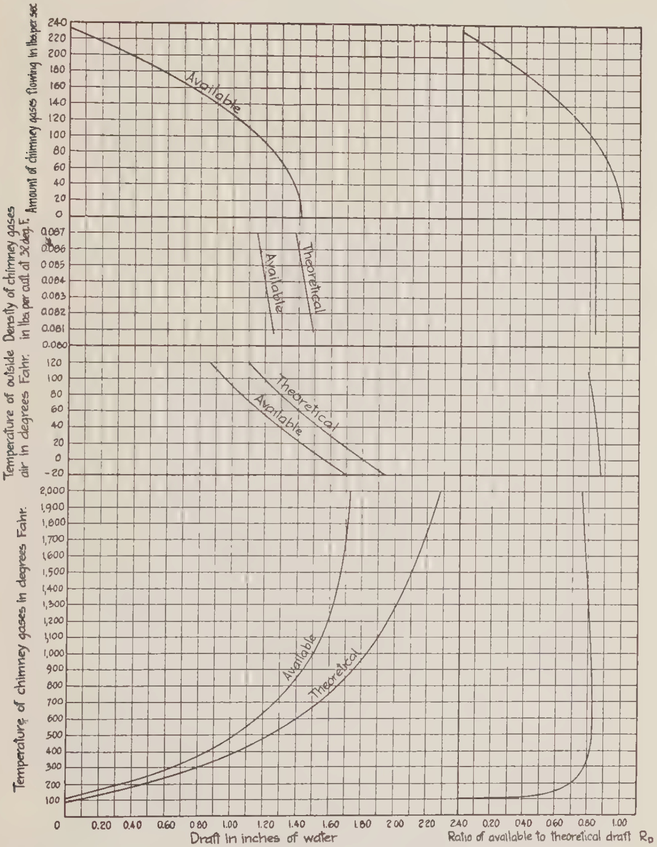

Fig. 68. Draft Performance of a 200 ft. x 10 ft. chimney.

case of a working chimney, the intensity of the theoretical draft is affected by:

1. Temperature of the chimney gases
2. Temperature of the outside air
3. Density of the chimney gases

Effect on the Theoretical Draft of a Working Chimney Due to a Variation in the Temperature of the Chimney Gases, the Temperature of the Outside Air, and the Density of the Chimney Gases

The chimney gas temperature varies, other factors remain unchanged:

t_c	D_t	t_c	D_t
60	0	1100	1.900
100	0.048	1200	1.962
200	0.486	1300	2.018
300	0.808	1400	2.068
400	1.056	1500	2.112
500	1.252	1600	2.152
600	1.412	1700	2.188
700	1.542	1800	2.220
800	1.654	1900	2.252
900	1.748	2000	2.280
1000	1.828		

Outside air temperature varies, other factors remain unchanged:

t_o	D_t	t_o	D_t
—20	1.944	50	1.470
—20	1.868	60	1.412
0	1.796	70	1.356
10	1.726	80	1.304
20	1.658	90	1.252
30	1.592	100	1.202
40	1.530	110	1.153

Density of chimney gases varies, other factors remain unchanged:

W_c	D_t	W_c	D_t
0.08071	1.496	.085	1.420
.081	1.492	.0855	1.412
.082	1.474	.086	1.402
.083	1.456	.087	1.384
.084	1.436		

Fig. 68 shows graphically the variation in the theoretical draft of a working chimney due to changes in the factors noted. Whence the theoretical draft of a working chimney varies:

1. Directly as the chimney gas temperature
2. Inversely as the outside air temperature
3. Inversely as the chimney gas density

Since it was assumed that the plant is at sea level and consequently under sea level atmospheric conditions, it follows that the atmospheric pressure affects the draft only when the altitude is changed, a condition which, of course, is impossible in the case of a working chimney. However, if the plant were built at higher elevations, then the theoretical draft would be affected considerably.

Atmospheric pressure varies, other factors remain unchanged:

E_1	P_o	B_o	D_t
0	14.70	29.92	1.412
385	14.50	29.50	1.392
851	14.25	29.00	1.368
1324	14.00	28.50	1.344
1806	13.75	28.00	1.320
2297	13.51	27.50	1.297
2797	13.26	27.00	1.274
3306	13.02	26.50	1.250
3828	12.78	26.00	1.227
4355	12.53	25.50	1.204
4894	12.28	25.00	1.180
5445	12.04	24.50	1.156
6008	11.79	24.00	1.133

The theoretical draft of a working chimney then varies:

1. Directly as the atmospheric pressure, or
2. Inversely as the elevation of the structure above sea level

It will be noted that the diameter of the chimney has no effect whatsoever on the intensity of the theoretical draft.

Available Draft

In addition to knowing the temperature of the chimney gases, the temperature of the outside air, the density of the chimney gases, and the elevation of the plant, in dealing with the available draft of a chimney, it is necessary to know also the amount of gases flowing through the chimney per second. This in turn requires a knowledge of the kind of fuel burned, together with an analysis of the fuel and also the rate of combustion per square foot of grate surface per hour, the diameter of the chimney, and the length of the friction duct or the distance between the bottom of the breeching opening and the top of the chimney. Therefore, let it be assumed that the fuel is coal showing the following analysis:

79 per cent carbon
5 per cent total hydrogen
2 per cent oxygen
2 per cent nitrogen
3 per cent sulphur
9 per cent ash

Also assume percentage of excess air as 50 per cent. Furthermore, let it be assumed that the boilers have a grate area of 800 sq.ft. and that the rate of combustion is 25 lbs. of coal per sq.ft. of grate surface per hour.

Now from the analysis of the coal, the total weight of dry air required per pound of coal equals:

$$W_{ta} = 11.52 \times 0.79 + 34.56 \left(0.05 - \frac{0.02}{8}\right) + 4.32 \times 0.03$$

$$= 9.10 + 1.64 + 0.13 = 10.87 \text{ lbs.}$$

For 50 per cent excess air:

$$W_{ta} = 10.87 \times 1.50 = 16.30 \text{ lbs.}$$

Whence, the total weight of the products of combustion per pound of coal equals

$$16.30 + 0.79 + 0.0475 + 0.03 = 17.17 \text{ lbs.}$$

The total weight of coal burned per hour equals:

$$800 \times 25 = 20{,}000 \text{ lbs.}$$

Finally, the total weight of the products of combustion equals

$$\frac{20000 \times 17.17}{3600} = 95 \text{ lbs. per second}$$

Loss Due to Velocity

From the data given heretofore, the loss of draft due to velocity equals:

$$h_v = 0.0000893 \; \frac{95^2 \times 1059.6}{14.7 \times (78.5)^2 \times 0.0855}$$
$$= 0.110 \text{ in. of water}$$

Loss of Draft Due to Friction

Let it be assumed that the bottom of the breeching opening is 20 ft. up from the grate level of the boilers. Whence, the length of the friction duct equals

$$200 - 20 = 180 \text{ ft.}$$

From the data given, the loss of draft due to friction equals

$$h_f = 0.0000893 \times 0.016 \times \frac{(95)^2 \times 1059.6 \times 180 \times 31.4}{14.7 \times (78.5)^3 \times 0.0855}$$
$$= 0.127 \text{ in. of water}$$

Available Draft

Finally, the available draft is equal to:

$$D_a = 1.412 - (0.110 + 0.127)$$
$$= 1.175 \text{ in. of water}$$

The intensity of the available draft, 1.175 in. of water, represents the actual amount of draft available at the breeching entrance of the chimney to overcome the resistances through the fuel bed, boiler, breeching, and bends. The intensity of the available draft is affected by the following factors:

1. Temperature of the chimney gases
2. Temperature of the outside air
3. Density of the chimney gases
4. Amount of gases flowing

Effect on Available Draft of a Working Chimney Due to a Variation in the Temperature of the Chimney Gases, the Temperature of the Outside Air, the Density of the Chimney Gases, and the Amount of Gases Flowing

Chimney gas temperature varies, other conditions remain unchanged:

t_c	D_t	h_v	h_f	h_v+h_f	D_a	R_D
0						
100	0.048	0.058	0.067	0.125	0	
200	.486	.068	.079	.147	0.339	0.698
300	.808	.078	.091	.169	.639	.791
400	1.056	.089	.103	.192	.864	.818
500	1.252	.100	.115	.215	1.037	.829
600	1.412	.110	.127	.237	1.175	.832
700	1.542	.120	.139	.259	1.283	.832
800	1.654	.131	.151	.282	1.372	.830
900	1.748	.141	.163	.304	1.444	.826
1000	1.828	.151	.175	.326	1.502	.822
1100	1.900	.162	.187	.349	1.551	.817
1200	1.962	.172	.199	.371	1.591	.811
1300	2.018	.183	.210	.393	1.625	.805
1400	2.068	.193	.222	.415	1.653	.800
1500	2.112	.203	.234	.437	1.675	.793
1600	2.152	.214	.246	.460	1.692	.786
1700	2.188	.224	.256	.480	1.708	.780
1800	2.220	.234	.270	.504	1.716	.773
1900	2.252	.244	.282	.526	1.726	.766
2000	2.280	.255	.294	.549	1.731	.760

Outside air temperature varies, other conditions remain unchanged:

t_o	D_t	h_v	h_f	h_v+h_f	D_a	R_D
—20	1.944	0.110	0.127	0.237	1.707	0.878
—10	1.868	.110	.127	.237	1.631	.873
0	1.796	.110	.127	.237	1.559	.869
10	1.726	.110	.127	.237	1.489	.863
20	1.658	.110	.127	.237	1.421	.857
30	1.592	.110	.127	.237	1.355	.851
40	1.530	.110	.127	.237	1.293	.845
50	1.470	.110	.127	.237	1.233	.838
60	1.412	.110	.127	.237	1.175	.832
70	1.356	.110	.127	.237	1.119	.825
80	1.304	.110	.127	.237	1.067	.818
90	1.252	.110	.127	.237	1.015	.811
100	1.202	.110	.127	.237	.965	.803
110	1.153	.110	.127	.237	.916	.795

Chimney gas density varies, other conditions remain unchanged:

W_c	D_t	h_v	h_f	h_v+h_f	D_a	R_D
0.08071	1.496	0.116	0.134	0.250	1.246	0.833
0.081	1.492	.116	.134	.250	1.246	.833
0.082	1.474	.115	.132	.247	1.227	.833
0.083	1.456	.113	.131	.244	1.212	.833
0.084	1.436	.112	.129	.241	1.195	.832
0.085	1.420	.111	.128	.239	1.181	.832
0.0855	1.412	.110	.127	.237	1.175	.832
0.086	1.402	.109	.126	.235	1.167	.832
0.087	1.384	.108	.125	.233	1.151	.831

Amount of gases flowing varies, other conditions remain unchanged:

W_a	D_t	h_v	h_f	h_v+h_f	D_a	R_D
0	1.412	0	0	0	1.412	1.000
20	1.412	0.005	0.005	0.010	1.402	.993
40	1.412	.019	.022	.041	1.371	.971
60	1.412	.044	.051	.095	1.317	.933
80	1.412	.078	.090	.168	1.244	.880
95	1.412	.110	.127	.237	1.175	.832
100	1.412	.122	.140	.262	1.150	.814
120	1.412	.176	.202	.378	1.034	.732
140	1.412	.239	.275	.514	.898	.637
160	1.412	.312	.359	.671	.741	.525
180	1.412	.396	.455	.851	.561	.400
200	1.412	.488	.561	1.049	.363	.257
220	1.412	.590	.680	1.270	.142	.100
232	1.412	.656	.756	1.412	0	0

Fig. 68 shows graphically the variation in the available draft of a working chimney due to changes in the factors noted. From the curves it will be seen that the available draft of a working chimney varies:

1. Directly as the chimney gas temperature
2. Inversely as the outside air temperature
3. Inversely as the chimney gas density
4. Inversely as the amount of gases flowing through the chimney

Since the theoretical draft, the loss due to velocity, and the loss due to friction all vary directly as the atmospheric pressure, or inversely as the elevation of the plant above sea level, it follows that the available draft varies in the same manner. Atmospheric pressure changes due to elevation, of course, can have no effect on the available draft of a working chimney since it is physically impossible to move a chimney from one elevation to another. Atmospheric pressure changes, however, will have a relative effect on the available draft of a working chimney when the draft is compared with that of a chimney of a similar size but located at a different altitude.

The curves at the right of Fig. 68 show graphically the variation in the ratio factor of the available draft to the theoretical draft, R_D. The curve for the ratio factor for the amount of gases flowing follows practically parallel to the curve for the variation in the available draft itself. When there are no gases flowing, the available draft is equal to the theoretical draft and the ratio factor is equal to 1. When 95 lbs. of gases are flowing per second, the ratio factor is equal to 0.83. When the amount is increased to about 232 lbs. per second, the available draft is zero and the ratio factor is 0. The line for the ratio factor for a variation in the density of the chimney gases is a straight line and is practically vertical, thereby signifying that the density of the chimney gases has no practical effect on the ratio factor. The curve for the ratio factor for a variation in the outside air temperature is slightly convex downwards and shows that the temperature of the outside air has only a relatively small effect on the ratio factor, about 10 per cent over a variation of 130 degrees.

In the case of the ratio factor for a variation in the temperature of the chimney gases, some startling facts are disclosed by the curve. It will be noted that the ratio factor gradually increases until a maximum is reached at a chimney gas temperature of approximately 640 deg. F. after which the ratio factor gradually decreases. This figure is the same at which a chimney will attain its maximum capacity. Now since

$$\frac{D_a}{D_t} = R_D$$

$$\text{then } D_a = R_D D_t$$

Therefore, the maximum relative available draft will be attained at a degree of chimney gas temperature which will make R_D a maximum, and which, in this particular example (when the density of the chimney gases is equal to 0.0855 lbs. per cu.ft. at 32 deg. F.) is approximately 640 deg. F. Of course, the available draft of a chimney, like the theoretical draft, increases as long as the chimney gas temperature increases but both above and below a temperature of approximately 640 deg. F. the relation between the two decreases.

In the above discussion, it has been assumed that the density and the temperature of the chimney gases remained constant regardless of the amount of gases flowing. In actual practice, however, the temperature of the chimney gases increases slightly as the amount of gases flowing increases, or what amounts to the same thing, as the rating of the boilers, or the amount of coal burned per square foot of grate surface per hour, increases. The temperature of the chimney gases also increases as the amount of excess air is increased.

The coefficient of friction, f, and the length of the friction duct, L, both affect the loss of draft due to friction and consequently the available draft. An increase in either one of these two factors will increase the intensity of the loss due to friction, which in turn will decrease the intensity of the available draft and likewise decrease the ratio factor. In the case of a chimney which has been in use for some time, the coefficient of friction doubtless will remain constant and will be equal to the value noted. As the height of the breeching is rarely changed, the length of the friction duct will always remain the same. When a new breeching opening is cut into the chimney at a height greater than that of the old opening, the length of the friction duct will be decreased, the loss due to friction will likewise be decreased and the available draft and the ratio factor will be increased.

Capacity Performance

A chimney is said to be working at actual, or normal rated, capacity when the amount of gases for which it was designed is being discharged. When more than this amount of gases is passing or being discharged, the chimney is working above its normal rated capacity, or is being "overworked"; when less than this amount is passing, the chimney is working below capacity. If the diameter of a chimney were made just large enough to accommodate the passage of the chimney gases at a certain velocity and at the same rate as they (the gases) are formed in the combustion chamber, if this rate of passage or discharge were continued uninterruptedly, and furthermore if the chimney gas temperature, the chimney gas density, and the outside air temperature remained constant, then the capacity performance of the chimney would be constant. Almost invariably, however, the diameter is made considerably larger than is actually required for ordinary operating conditions because at times the chimney may be required to accommodate an increased amount of gases per second. This happens when the rate of combustion, or the rating of the boilers, is increased over that for normal requirements. As a result, the chimney is ordinarily working considerably below its normal rated capacity. Only on rare occasions will a properly designed chimney be required to work above its actual capacity. Furthermore, the temperature of the chimney gases, the density of the chimney gases, and the temperature of the outside air may vary from time to time and as a consequence the capacity performance will be greatly affected.

Analyzing the capacity performance of a working chimney may appear to be somewhat of a complicated process but it can be made quite simple by disregarding some of the relatively less important factors or conditions. The general equation for the capacity of a chimney is as follows:

$$W_a = AR_cK_{wc}K_t \sqrt{H}$$

in which $A = 0.7854D^2$

$$R_c = \frac{0.215 \sqrt{\frac{P_o T_c h_v}{W_c}}}{8.02 \sqrt{H\left(\frac{C_t T_c}{T_o} - 1\right)}}$$

$$K_{wc} = 3942 W_c$$

and $$K_t = \sqrt{\frac{C_t T_c - T_o}{T^2_c T_o}}$$

From these equations it will be seen that the capacity performance of a chimney is affected by the following factors or conditions:

1. Temperature of the chimney gases.
2. Temperature of the outside air.
3. Density of the chimney gases.

The capacity performance may also be affected by the conditions noted in the chapter on "Capacity." As in the case of draft performance, it is impossible to express these conditions in numerical terms and for this reason their exact effect cannot be determined except from observation.

Using the same data given heretofore, the actual, or the normal rated, capacity of a 200 ft. x 10 ft. chimney is found as follows:

$$A = 0.7854\ (10)^2 = 78.54 \text{ sq.ft.}$$

$$V_t = 8.02 \sqrt{200\left(\frac{0.944 \times 1059.6}{519.6} - 1\right)}$$

$$= 109 \text{ ft. per sec.}$$

Assuming that the loss of draft due to velocity h_v, is equal to 0.11 in of water as determined heretofore:

$$V_a = 0.215\sqrt{\frac{14.7 \times 1059.6 \times 0.11}{0.0855}}$$

$$= 30.6 \text{ ft. per sec.}$$

$$\text{Whence } R_c = \frac{V_a}{V_t} = \frac{30.6}{109} = 0.281$$

$$K_{wc} = 268.2 \times 14.7 \times 0.0855 = 337$$

$$K_t = \sqrt{\frac{0.944 \times 1059.6 - 519.6}{(1059.6)^2 \times 519.6}}$$

$$= 0.0009077$$

Whence, finally

$$W_a = 78.54 \times 0.281 \times 337 \times 0.0009077 \times 14.14$$

$$= 95.4 \text{ lbs. per sec.}$$

Since the furnace is generating gases at the rate of 95.4 lbs. per second, the chimney is working at its actual, or normal rated, capacity and it is functioning properly under the exact conditions for which it was designed. When, however, more than 95.4 lbs. of gases are generated by the furnace and are consequently being discharged by the chimney per second, the chimney is then being worked above its normal rated capacity, or is "overworked" or "overloaded"; but when less than this amount of gases is being passed, the chimney is working below its actual capacity. As a general rule, most chimneys are ordinarily working considerably below their actual capacity, as stated heretofore, because it is necessary to make the diameter sufficiently large to accommodate the increased amount of gases when the rate of combustion, or the rating of the boilers, is increased to the maximum.

Let us now investigate the effect on the capacity performance of a chimney when the amount of gases generated by the furnace varies. In this analysis it will be assumed that the gases generated at a certain rate in the furnace pass on into the chimney and must be accommodated or "handled" by the chimney at this same rate, and also that the density and temperature of these gases remain unchanged regardless of the amount generated. This assumption is not strictly true since the temperature of the gases increases somewhat as the rate of combustion increases, but the variation is not of sufficient consequence that it need be taken into account.

In the example under discussion, gases are being generated in the furnace at the rate of 95.4 lbs. per second, pass on through the rest of the installation and are finally discharged by the chimney at this same rate. The gases ascend in the chimney at the velocity of 30.6 ft. per second, resulting in a loss of draft due to friction of 0.127 in. of water. Now it is evident that when less than 95.4 lbs. of gases per second are discharged, the velocity of the velocity of the gases in the chimney will be less and also the loss of draft due to friction will be less, and vice versa. The velocity of the chimney gases should not be confounded with the velocity of the gases in the furnace or the boiler. There is no relation between the two.

Assuming that the temperature and density of the chimney gases remains constant, and also that the temperature of the outside air remains unchanged, it is obvious that the actual velocity of the chimney gases will be the only factor affected by a variation in the amount of gases flowing. This in turn affects the value of R_c, or the "efficiency" of the chimney. As stated in a previous paragraph, the loss of draft due to friction and the loss due to velocity, increase as the velocity of the chimney gases increases, and the available draft becomes less as a result. Hence, the value of R_c increases and the value of R_D decreases as the amount of chimney gases increases. Provided there continued to be sufficient draft to supply air to the fuel bed, the working velocity of the chimney gases would be increased up to 109 ft. per second, at which point the chimney would be 100 per cent efficient. Long before this velocity is reached, however, the available draft will become zero, no air can be supplied to the fuel bed, and the actual capacity of the chimney will suddenly drop to zero since no gases would be flowing. Such a state of affairs of course is purely theoretical and no such condition would ever be encountered in actual practice.

The amount of chimney gases flowing varies, other conditions remain unchanged:

$W=W_a$	h_v	V_a	R_c
0	0	0	0
10	0.0014	3.2	0.029
20	.0056	6.4	.059
30	.0126	9.7	.089
40	.0225	12.9	.118
50	.0352	16.1	.148

$W = W_a$	h_v	V_a	R_c
60	.0506	19.3	.177
70	.069	22.5	.207
80	.090	25.8	.236
90	.114	29.0	.266
95	.127	30.6	.281
100	.141	32.3	.296
110	.170	35.5	.326
120	.202	38.6	.354
130	.238	42.0	.385
140	.276	45.1	.414
150	.316	48.4	.444
160	.360	51.5	.472
170	.406	54.9	.503
180	.455	58.0	.532
190	.508	61.2	.561
200	.563	64.3	.590
210	.620	67.2	.616
220	.680	70.9	.650
232	.756	74.6	0.685

Fig. 69 shows these results graphically. The values of h_v, V_a, and R_c increase as the amount of chimney gases flowing increases. When the quantity of gases flowing reaches 232 lbs. per second, the sum of the losses of draft due to friction and to velocity will be equal to the theoretical draft of the chimney, the available draft will be zero, and since no air can be supplied to the fuel bed, no gases will be generated and consequently the capacity will gradually drop to zero. The actual velocity of the chimney gases at this point will be equal to:

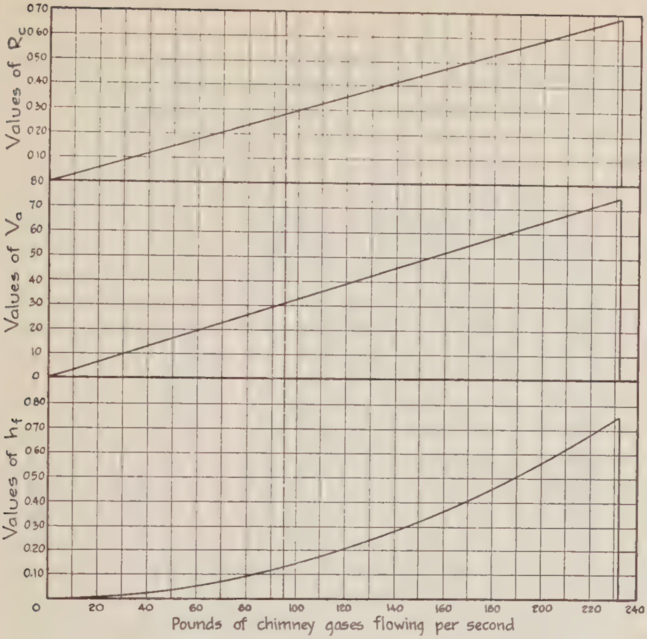

Fig. 69. Effect on h_f, V_a, and K_c Due to a Variation in the Value of W_a.

Based on H — 200 ft., D — 10 ft., t_c — 600 deg. F., t_o — 60 deg. F., f — 0.016, W_c — 0.0855, and a circular section.

$$V_a = 0.215 \sqrt{\frac{14.7 \times 1059.6 \times 0.656}{0.0855}}$$

$$= 74.6 \text{ ft. per sec.}$$

Fig. 70 shows the relative effect of the quantity of gases flowing in a chimney upon the draft and the capacity, based on terms of R_D and R_c.

The three major factors affecting the capacity performance of a working chimney are the temperature of the chimney gases, the temperature of the outside air, and the density of the chimney gases. The coefficient of friction, of course, is constant for any working chimney, but it may vary between a masonry and an unlined new steel chimney, for example. However, the inside surface of practically all chimneys which have been in operation for some time, regardless of the material of which they are constructed, is well covered with a thick layer of soot, and for this reason it may be assumed that the coefficient of friction is a constant quantity at all times. The atmospheric pressure can affect the capacity performance only during a change in the weather. There will, however, be a relative difference in the capacity performance for the same size chimney but built at different altitudes. The loss of draft due to friction is an arbitrary quantity depending upon the quantity of gases flowing and the temperature of the gases.

Effect on Capacity Performance of a Working Chimney Due to a Variation in the Temperature of the Chimney Gases, the Temperature of the Outside Air, and the Density of the Chimney Gases

Chimney gas temperature varies, other factors remain unchanged:

t_c	V_t	h_v	V_a	R_c	K_{wc}	K_t	W_a
100	12.8	0.004	3.6	0.281	337	0.000231	24.3
200	50.5	0.044	14.2	0.281	337	0.000674	70.9
300	69.9	0.074	19.6	0.281	337	0.000811	85.3
400	85.0	0.096	23.9	0.281	337	0.000871	91.6
500	97.8	0.114	27.5	0.281	337	0.000898	94.5
600	109.0	0.127	30.6	0.281	337	0.0009077	95.4
641.2	113.4	0.133	31.9	0.281	337	0.0009084	95.6
700	119.3	0.140	33.5	0.281	337	0.000907	95.4
800	128.7	0.150	36.0	0.281	337	0.000900	94.7
900	137.5	0.158	38.6	0.281	337	0.000891	93.7
1000	145.2	0.166	40.8	0.281	337	0.000880	92.6
1100	153.7	0.172	43.2	0.281	337	0.000868	91.3
1200	160.9	0.178	45.2	0.281	337	0.000855	89.9
1300	168.0	0.183	47.2	0.281	337	0.000842	88.5
1400	174.9	0.188	49.2	0.281	337	0.000829	87.2
1500	181.4	0.191	51.0	0.281	337	0.000816	85.8
1600	187.8	0.195	52.8	0.281	337	0.000803	84.5
1700	193.8	0.198	54.5	0.281	337	0.000791	83.2
1800	199.8	0.201	56.1	0.281	337	0.000780	82.1
1900	205.5	0.204	57.7	0.281	337	0.000769	80.9
2000	211.2	0.207	59.3	0.281	337	0.000758	79.7

Outside air temperature varies, other factors remain unchanged:

t_o	V_t	h_v	V_a	R_c	K_{wc}	K_t	W_a
—40	133.4	0.191	37.6	0.281	337	0.001110	116.7
—20	128.0	.177	36.0	.281	337	.001066	112.1
0	123.0	.163	34.6	.281	337	.001023	107.6
20	118.2	.150	33.3	.281	337	.000983	103.4
40	113.5	.139	32.0	.281	337	.000945	99.4
60	109.0	.127	30.6	.281	337	.000908	95.4
80	104.8	.118	29.4	.281	337	.000872	91.7
100	100.6	.109	28.3	.281	337	.000837	88.0
110	98.6	.105	27.8	.281	337	.000820	86.2

Chimney gas density varies, other factors remain unchanged:

W_c	C_t	V_t	h_v	V_a	R_c	K_{wc}	K_t	W_a
0.08071	1.000	115.6	0.134	32.5	0.281	318.2	0.000962	95.4
0.081	.996	115.2	.134	32.4	.281	319.3	.000959	95.4
0.082	.984	114.8	.132	32.2	.281	323.2	.000947	95.4
0.083	.972	112.5	.131	31.6	.281	327.2	.000936	95.4
0.084	.961	111.1	.129	31.2	.281	331.1	.000925	95.4
0.085	.950	109.7	.128	30.8	.281	335.1	.000914	95.4
0.0855	.944	109.0	.127	30.6	.281	337.0	.000908	95.4
0.086	.939	108.4	.126	30.5	.281	339.0	.000902	95.4
0.087	.928	107.1	.125	30.2	.281	343.0	.000891	95.4

Fig. 71 shows these results graphically. It will be seen that only two major factors affect the capacity performance of a chimney, viz.: the temperature of the chimney gases and the temperature of the outside air.

The capacity performance of a chimney increases as the chimney gas temperature increases until a maximum is reached at a temperature of 641.2 deg. F., after which the capacity performance gradually decreases. It should be recalled that this maximum figure is for an outside air temperature of 60 deg. F. and a chimney gas density of 0.0855 lbs. per cu.ft. at 32 deg. F. The maximum will occur at a chimney gas temperature of 702.7 deg. F. when the outside air temperature is 100 deg. F., and at 514.1 deg. F. when the outside air temperature is 0 deg. F., both based on $W_c = 0.0855$. The value of both V_t and V_a increases in the same ratio so that the value of R_c remains constant regardless of the temperature of the chimney gases. Since the height and the diameter of the chimney, as well as the values of R_c and K_{wc}, all remain constant, the capacity performance then

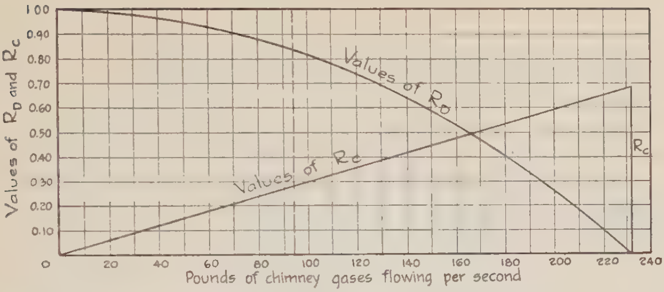

Fig. 70. Comparative Effect on K_D and K_C Due to a Variation in W_a.
Based on H — 200 ft., D — 10 ft., t_c — 600 deg. F., t_o — 60 deg. F., f — 0.016, W_c — 0.0855, and a circular section.

will vary as the value of K_t which in turn varies as the temperature of the chimney gases, the density of the chimney gases, and the temperature of the outside air. It will be seen in a later paragraph that the density of the chimney gases has no material effect on the capacity performance, hence the capacity performance varies only as the temperature of the chimney gases and the temperature of the outside air.

An inspection of the table and Fig. 71 will disclose the fact that between chimney gas temperatures of 500 and 700 deg. F. there is very little variation in the capacity of performance due to a change in the chimney gas temperature. Below 500 deg. F. the capacity performance diminishes rapidly until it becomes zero at about 60 deg. F. or the temperature of the outside air. Above 700 deg. F. the capacity performance diminishes but at a relatively slower rate. This fact is of extreme im-

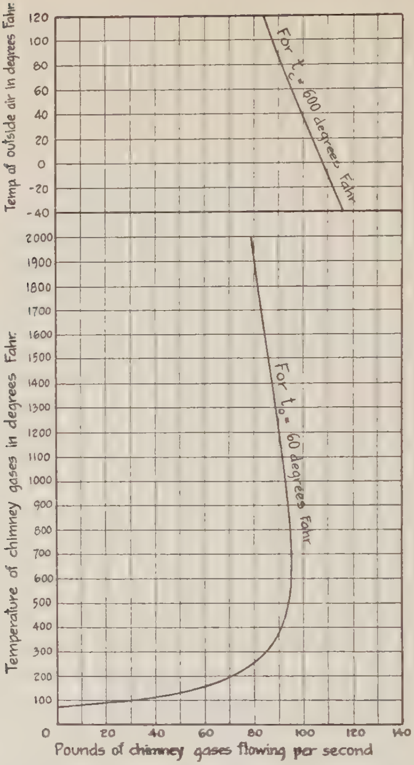

Fig. 71. Capacity Performance of a 200 ft. x 10 ft. Chimney. Based on t_c — 600 deg. F., t — 60 deg. F., f — 0.016, W_c — 0.0855, and a circular section.

portance, particularly in installations where economizers are used. Oftentimes in such installations the temperature of the chimney gases is around 350 to 400 deg. F. and as a result the capacity performance is reduced considerably.

When the temperature of the outside air varies, the capacity performance varies in the same manner as the draft performance, that is to say, each increases as the outside air temperature decreases, other conditions remaining constant. This variation is shown graphically by the upper curve in Fig. 71. This curve is slightly concave upwards. The capacity performance is approximately 12.8 per cent greater for an outside air temperature of 0 deg. F., and 22.4 per cent greater for an outside air temperature of —40 deg. F., but approximately 7.8 per cent less for an outside air temperature of 100 deg. F., than that for an outside air temperature of 60 deg. F. As in the case of the temperature of the chimney gases, the value of both V_t and V_a vary in the same ratio, so that the value of R_c remains constant regardless of the temperature of the outside air. Since the height and diameter of the chimney, as well as the values of R_c and K_{wc} remain unchanged regardless of the temperature of the outside air, the capacity performance varies as the value of K_t.

The density of the chimney gases has no material effect on the capacity of a chimney. The values of V_t and V_a vary in the same ratio and as a result the value of R_c is unchanged. The value of K_{wc} varies directly as W_c but the value of K_t varies inversely in the same ratio, whence the product of R_c, K_{wc} and K_t for the various values of W_c, together with A and H, is a constant quantity.

Summary

The draft performance of a working chimney is affected by a variation in the operating conditions as follows:

1. Increases as the chimney gas temperature increases
2. Decreases as the outside air temperature increases
3. Decreases as the density of the chimney gases increases

The capacity performance of a working chimney is affected by a variation in the operating conditions as follows:

1. Increases up to a certain maximum and then decreases as the temperature of the chimney gases increases
2. Decreases as the temperature of the outside air increases
3. Unaffected by the density of the chimney gases

It may be well to recall the fact that the performance of a working chimney, as has been discussed in this chapter is based on a specific size of chimney 200 ft. high by 10 ft. internal diameter which was designed for a chimney gas temperature of 600 deg., an outside air temperature of 60 deg. F., a chimney gas density of 0.0855 lbs. per cu.ft. at 32 deg. F., sea level atmospheric conditions, a coefficient of friction of 0.016, and which is capable of discharging 95.4 lbs. of chimney gases at a velocity of 30.6 ft. per sec. In other words, a specific size of chimney together with an arbitrary set of operating conditions was investigated, and general conclusions were drawn for this particular case. This same method, however, may be applied to any other size of chimney and any other combination of operating conditions for which this particular size was designed. The results as enumerated under the summary will be identical regardless of the size of the chimney or the values assigned to the various operating conditions. That is to say, the temperature of the chimney gases, for example, will affect the draft and capacity performance in the same manner regardless of the size of the chimney.

In addition to the observable factors noted heretofore, the performance of a chimney may be affected by various other factors which, however, cannot be expressed in numerical quantities but the effect of which can be ascertained only by observation. Several of these factors will now be discussed in detail.

The material of which a chimney is constructed, that is steel, brick, or concrete, unquestionably has some effect on the performance of a chimney. If a steel chimney is unlined, the radiation will be relatively high and the temperature of the chimney gases will be correspondingly lower as a result. Since the radiation varies as the thickness of the walls of the chimney, all other factors remaining constant, it follows that adverse performance varies as steel, concrete and brick, and in the order named; the average relative thickness of the chimney walls also being in the order named.

The character of the inside surface of the chimney determines the coefficient of friction which in turn affects the performance. The walls of a new unlined steel chimney have by far the greatest degree of smoothness, followed by those of a new concrete and a new brick chimney. The walls of a newly constructed brick chimney present a comparatively rough surface due to the offsets caused by a change in the wall thickness. The coefficient of friction then will vary as the degree of roughness, being greatest for a brick chimney and least for an unlined steel chimney. It should be noticed that the word "new" was used in describing the structure. In the case of a chimney which has been in use for some time, the walls of a chimney, regardless of the material of which it is built, are covered with a thick layer of soot and the relative degree of roughness is thereby eliminated. All inside surfaces may then be described as "sooty" surfaces and it seems reasonable to assume that the coefficient of friction will be the same for all three kinds of surfaces. Since a surface covered with soot is by no means a smooth surface, it furthermore seems reasonable to assume that the coefficient of friction will be at least as great as that for a brick chimney. A value of $f = 0.016$ has been used throughout the various examples, and theory of this book, and the results obtained accord well with those found in actual practice. There is great need for more experimenting on this subject in order to determine more accurately the value of this much neglected point.

The physical conditions of a chimney, that is the presence or absence of cracks, has a very important effect on the performance. Cracks in a chimney admit the cooler outside air which in turn lowers the temperature of the chimney gases and also increases the amount of gases flowing. Cracks in a chimney are uncalled for and are the result of carelessness in either design or construction. It is possible to build chimneys so that they will not crack, but when cracks do appear they should be closed at once. Air may also be admitted through improperly sealed joints. This, too, is the result of improper construction and is particularly true of brick chimneys. The above remarks apply only to concrete and brick chimneys.

The height of the lining of a chimney has been the subject of much discussion. The theory has been advanced by some engineers that the primary purpose of the lining is to help reduce the radiation. This theory, however, is open to some question. In the case of a steel chimney, the lining without question does reduce radiation to a very great extent but in the case of properly constructed concrete and brick chimneys the lining, in all probability, has but little effect on the radiation. If it is true that the lining helps to reduce radiation, then the performance of a chimney varies as the height and thickness of the lining. After all the question of radiation is of relatively small importance for the reason that the chimney gases are inside of a chimney for such a relatively short period of time that they cannot be cooled sufficiently to cause any appreciable effect on the performance.

When a lining is built inside of a chimney, an air space of from two to four inches is ordinarily left between the lining itself and the shaft, except in the case of a steel chimney where the lining is laid in close contact with the steel shell. The purpose of this air space is to provide room for contraction and expansion. It is thought by some that the presence of an air space will aid materially in reducing radiation but this theory is open to argument. In case this theory is true, it is only of relatively small importance. It is true that a dead air space of hot air is a poor conductor of heat but the percentage of radiation which will be prevented by this arrangement is in all probability very low.

The type of construction around the top of the chimney should be such that the wind will be given an upward and not a downward direction. Strong winds tend to flatten the escaping column of gases and this results in a downward force which in turn produces a back-pressure. This will diminish the available draft and reduce the capacity performance.

Another source of trouble commonly encountered but seldom remedied is a loosely fitting breeching at the chimney opening. The breeching at the opening should be well calked with asbestos or other material. Leakages will then be reduced to a minimum and the performance will not be affected.

Numerous other factors which may tend to affect the performance of a chimney in one way or another may be found in the chapter on available draft.

CHAPTER XIII

RELATION BETWEEN HEIGHT AND DIAMETER AND A TYPICAL EXAMPLE

As has been stated previously, a thorough analysis of the draft and capacity conditions of a chimney, such as has been developed heretofore, is made for two definite purposes, viz:

1. To investigate the draft and capacity performance of a working chimney.
2. To determine the required height and diameter of a projected chimney.

The draft and capacity performance of a working chimney were discussed in detail in the preceding chapter. The operating conditions as gathered from observation were applied to the structure, the size of which is definitely known, and the behavior of the chimney operating under these conditions was examined. This process in itself is a relatively simple one inasmuch as all of the required data and information can be ascertained practically without question, and the substitutions in the equations, together with the subsequent reductions, present no particularly difficult problem.

In the case of determining the required height and diameter of a projected chimney which is to satisfy certain arbitrarily selected operating conditions, however, a far more difficult problem is encountered. While most of the operating factors or conditions are known either from observation or computation, there are two factors, the loss due to velocity and the loss due to friction, which are dependent in one way or another upon the diameter of the chimney itself. In other words, determining the required size of a chimney involves a problem the solution of which depends upon the answer itself. This condition implies a certain amount of the cut-and-try process until all factors have been satisfied, unless some relation is established between velocity and size.

The height of a properly designed chimney, as has been stated, is dependent upon the total amount of draft required, and the diameter upon the amount of gases flowing. But in addition to this, there are interrelations which must be taken into consideration, that is to say, the value of both the height and the diameter depend upon each other. By a judicious selection of the trial values for the height and diameter, however, the solution of the problem will be greatly simplified. Also, certain relations can be established which will materially aid in arriving at the proper size.

The required height of a chimney is given by the equation:

$$H = \frac{D_t}{K_D}$$

$$= \frac{h_F + h_B + h_{Br} + h_T + h_v + h_f}{6.43P_o\left(\frac{W_o}{T_o} - \frac{W_c}{T_c}\right)}$$

and the diameter, in the case of a circular chimney, by the equation:

$$D = \sqrt{\frac{W_a}{\frac{\pi}{4} R_c K_{wc} K_t \sqrt{H}}} = \sqrt{\frac{W_a}{\frac{\pi}{4} \frac{V_a}{V_t} K_{wc} K_t \sqrt{H}}}$$

$$\text{or } D = 0.195 \sqrt{\frac{W_a\, T_c}{W_c\, V_a\, P_o}}$$

Velocity of Chimney Gases

The required height, then, is equal to the sum of the various losses of draft throughout the installation, or the required amount of draft necessary to cause the requisite amount of gases to flow through the installation, divided by the theoretical draft per foot of chimney. These various losses of draft vary as the square of the velocity at the various sections. These various velocities, in turn, can be reduced to a common velocity, such as that of the velocity of the chimney gases. On this basis, the equation for the required height of a chimney may be written as follows:

$$H = \frac{V_a^2 \left[h'_F + h'_B + 0.10\, W_c \quad \frac{P_o}{T_c} \left(\frac{fl}{C_{br}} + X_T + 1 + \frac{4fL}{D} \right) \right]}{6.43 P_o \left(\frac{W_o}{T_o} - \frac{W_c}{T_c} \right)} \qquad 261$$

in which V_a = actual or working velocity of the chimney gases in feet per second,

h'_F = a constant which, when multiplied by the square of the chimney gas velocity, equals the loss through the fuel bed,

h'_B = a constant which when multiplied by the square of the chimney gas velocity equals the loss through the boiler,

X_T = number of turns or bends.

Thus it will be seen that both the height and the diameter of a chimney depend upon the velocity of the chimney gases. The velocity of the chimney gases is given by the equation:

$$V_a = \frac{W_a T_c}{33.44\ A\ W_c P_o}$$

In this equation the values of W_a, T_c, P_o, and W_c are known but the value of A is unknown, of course, since it is one of the objectives in the problem. Now since both V_a and A are unknown, either a value must be assumed for V_a and A computed, or a value must be assumed for A and V_a computed. The flow of gases in a chimney installation is similar, in most respects, to the flow of water in a pipe. The velocity varies as the area; the greater the area, the less the velocity, and vice versa. Or in other words, in a chimney with a relatively large area, the gases have a lower velocity than those in a chimney with a relatively small area, other conditions such as height, temperature, density, and amount of gases flowing, remaining constant. It is therefore necessary to eliminate either the velocity or the area from temporary consideration. Since the area of the chimney, or diameter in the case of a circular chimney, is one of the objectives in the problem, it will be eliminated and dissociated from velocity.

Now the question arises: upon what does the working velocity of the chimney gases depend, or, how is it to be determined? Is there such a condition as an economical velocity of the chimney gases? It is obvious that if the working velocity is assumed relatively high, the losses due to velocity and to friction will likewise be great and a relatively high chimney will be required as a consequence. On the other hand, if the working velocity is assumed relatively low, the losses due to velocity and to friction will be small and a relatively low chimney will be the result. All other conditions being equal, the former will require a relatively small diameter, or area, and the latter a relatively large one. It is evident that unless some relation is established between the working velocity and some other related factor, numberless combinations of heights and diameters could be made up. Several authorities have apparently delved into this very important subject and some have advanced the opinion, or theory, that, of the various combinations, the most economical size is the one whose product of diameter by height is least. The question of economical size, in the final analysis, resolves itself into a question of cost. It is the writer's contention that this is only a relative issue for the reason that there are so many other factors such as location of chimney as regards section of country, materials of which it is built such as steel, brick or concrete, design, etc., which have a far greater effect on the cost. Then, too, it would be a tremendous job to work out a sufficient number of sizes for a set of working conditions in order to select such an economical size.

The logical method of determining the working velocity of the chimney gases is to compute the theoretical velocity and multiply this quantity by R_c, or the "efficiency factor" of the chimney. The theoretical velocity of the chimney gases, however, is dependent upon the height of the chimney which is also one of the objectives in the problem and consequently is unknown, not even approximately, at the outset.

It is obvious, then, that the working velocity must be based on some factors or conditions which are known, or which can be ascertained fairly closely.

Now since $A = \dfrac{W_a\ T_c}{33.44\ V_a\ W_c\ P_o}$

then $D = 0.195\ \sqrt{\dfrac{W_a\ T_c}{V_a\ W_c\ P_o}}$

Likewise from the equation for the loss of draft due to velocity:

$$A^2 = \frac{0.0000893\ W^2_a\ T_c}{W_c\ h_v\ P_o} \tag{262}$$

Whence $$D = \sqrt[4]{\frac{0.0000893\ W^2_a\ T_c}{\left(\frac{\pi}{4}\right)^2\ W_c\ h_v\ P_o}} \tag{263}$$

Equating the above two equations for D:

$$\sqrt[4]{\frac{0.0000893\ W_a\ T_c}{\left(\frac{\pi}{4}\right)^2\ W_c\ h_v\ P_o}} = 0.195\ \sqrt{\frac{W_a\ T_c}{V_a\ W_c\ P_o}} \tag{264}$$

Whence $$V_a = \sqrt{10\ \frac{T_c h_v}{P_o W_c}} \tag{265}$$

Assuming $P_o = 14.7$ lbs. per sq.in. for sea level atmospheric pressure

and $W_c = 0.0855$ lbs. per cu.ft. at 32 deg. F.

$$V_a = \sqrt{8T_c h_v} \tag{266}$$

The equation for the working velocity of the chimney gases has now been simplified to the extent that only two factors remain, viz.: the temperature of the chimney gases and the intensity of the loss due to velocity. The former is known or can be easily ascertained but the latter cannot and it is therefore necessary to make an assumption for this factor.

For the purpose of argument, assume:

$$h_v = 0.10 \text{ inches of water}$$

$$\text{Then } V_a = \sqrt{0.8T_c} \tag{267}$$

Finally, assuming a chimney gas temperature of 641.2 deg. F. which is the temperature at which a chimney will attain its maximum capacity,

$$V_a = \sqrt{0.8 \times 1100.8}$$

$$= 29.6, \text{ or, practically, } 30 \text{ ft. per. sec.}$$

This value, 30 ft. per second, may then be considered as an arbitrary selection for the velocity of the chimney gases in all preliminary calculations for the size of a chimney. This value, of course, varies as the temperature of the chimney gases, the loss of draft due to velocity, the density of the chimney gases, and the elevation of the plant, but none of these factors, with the exception of the loss due to velocity, as encountered in average practice, will affect the velocity to an appreciable extent. The assumption of 0.10 in. of water for the loss due to velocity is a purely arbitrary one. It is, however, a fair assumption and gives results which are in accord with sound practice. At any rate it forms the starting point in the solution of a problem, an attack on which would be practically impossible by any other method.

Since a new or projected chimney will be required to serve the plant when all of the operating conditions are at a maximum at the same time, great care should be exercised in determining and selecting the figures for these maximum conditions. In the case of the loss of draft through the fuel bed, that value should be selected which represents the loss for the maximum rate of combustion and not that for the normal rate. Again, a value for the loss of draft through the boiler should be selected which represents the loss when the boiler is being operated at its maximum capacity and not that at its normal rating. The various other losses of draft should be computed on the basis of the maximum amount of gases flowing through the installation, which, in turn, involves the maximum rate of combustion, and not the amount of gases which are flowing for a normal rate of combustion. These facts should be constantly kept in mind. Often wrong assumptions and data are used in determining the required size and serious operating troubles are subsequently encountered as a result.

Information Required

The following information or data are required in determining the required size of a projected chimney:

1. Temperature of the chimney gases
2. Temperature of the outside air
3. Density of the chimney gases
4. Elevation of the plant above sea level
5. Make and maximum rating of the boilers
6. Square feet of grate surface
7. Kind of fuel used
8. Analysis of fuel
9. Maximum rate of combustion
10. Length of breeching
11. Number of bends in breeching
12. Height of bottom of breeching above grate level

It is not necessary to know the horsepower of the boilers. As a matter of fact, it is to the advantage of the designer if this information is withheld completely. It has been the custom to base the size of a chimney on the horsepower of the boilers, and the size is usually selected from a table which has been constructed on this basis. This practice is abominable and should be discontinued. It is safe to say that the great majority of the average operating troubles of a steam plant are due to a badly designed chimney, the size of which has been selected from such tables.

Typical Example

The following data will be assumed to represent the operating conditions of a steam plant for which the size of a new chimney is to be determined.

600 deg. F., chimney gas temperature
60 deg. F., outside air temperature
0.0855 density of the chimney gases in lbs. per cu. ft. at 32 deg. F.

700 feet above sea level, elevation of the plant
250 per cent, maximum rating of the boilers
800 sq.ft., total grate surface
Fuel—Pennsylvania semi-bituminous coal,
Analysis of coal:

78 per cent carbon
5 per cent total hydrogen
2 per cent oxygen
3 per cent nitrogen
4 per cent sulphur
8 per cent ash

35 lbs. of coal per sq.ft. of grate surface per hour, maximum rate of combustion
100 ft., distance from farthest boiler to chimney, straight breeching with no bends.
20 ft., height of bottom of breeching above grate level of boilers.
Boilers fed by underfeed stokers.

Amount of Gases Flowing

In computing the required size of a new or projected chimney, it is necessary, first of all, to determine the total weight of gases generated in the furnace per unit of time. From the analysis of the coal given, the theoretical weight of dry air required per lb. of coal equals:

$$
\begin{aligned}
W_{ta} &= 11.52 \times 0.78 + 34.56\left(0.05 - \frac{0.02}{8}\right) + 4.32 \times 0.04 \\
&= 8.99 + 1.64 + 0.17 \\
&= 10.8 \text{ lbs.}
\end{aligned}
$$

Since stokers are used, a maximum of 50 per cent excess air will be assumed. Hence the total weight of air required to burn one pound of coal equals:

$$W_{Ta} = 10.8 \times 1.5 = 16.2 \text{ lbs.}$$

Whence the total weight of the products of combustion due to the combustion of one pound of coal equals:

$$W_{tp} = 16.20 + 0.78 + 0.0475 + 0.04$$
$$= 17.07 \text{ lbs.}$$

The total weight of coal burned per hour at the maximum rate of combustion, 35 lbs. per sq.ft. of grate surface per hour, equals:

$$800 \times 35 = 28{,}000 \text{ lbs.}$$

Finally, the total weight of the products of combustion equals:

$$\frac{28{,}000 \times 17.07}{3600} = 132.8, \text{ or practically } 133, \text{ lbs. per sec.}$$

The furnace generates the gases at the rate of 133 lbs. per second and these gases must of necessity pass through the breeching and up through the chimney at this same rate. The temperature of these gases will be assumed to be uniform throughout the breeching and the chimney.

The problem at hand, stated in a few words, is to design a chimney the height of which will be such that sufficient draft will be created to overcome all the various losses of draft throughout the installation and cause the necessary amount of air to flow into the fuel so that 35 lbs. of coal will be burned per sq.ft. of grate surface per hour and 133 lbs. of gases will be generated per second, and the diameter, or area, of which will pass these gases at this same rate at a predetermined velocity.

Required Draft

Loss of draft through the fuel bed. The loss of draft through the fuel bed for a maximum rate of combustion of 35 lbs. of Pennsylvania semi-bituminous coal per sq.ft. of grate surface per hour, as given by Fig. 38, is equal to 0.58 in. of water. It should be noted that this loss of draft is based on the maximum rate of combustion and not on the normal rate.

Loss of draft through the boiler. The loss of draft through the boiler will be assumed at 0.80 in. of water when the boiler is run at its maximum rating, 250 per cent. This intensity of the loss of draft can be supplied accurately by the boiler manufacturer.

Velocity of gases in breeching and chimney. The velocity of the gases in the breeching and chimney, as given by equation 265, is equal to:

$$V_a = \sqrt{10 \times \frac{1059.6 \times h_v}{14.33 \times 0.0855}}$$

$$= \sqrt{8650 h_v}$$

Assuming $h_v = 0.10$ in. of water

$$V_a = \sqrt{8650 \times 0.10}$$

$$= 29.4 \text{ ft. per sec.}$$

This velocity will now be used in determining the various losses of draft throughout the installation.

Loss of draft through the breeching. The size of the breeching must be determined before the loss through it can be ascertained. The only data at hand regarding the breeching is that it is 100 ft. long, has no turns or bends, and must pass 133 lbs. of gases per second at a predetermined velocity of 29.4 ft. per second. Now the area of the breeching is equal to:

$$A = \frac{133 \times 1059.6}{33.44 \times 29.4 \times 0.0855 \times 14.33}$$
$$= 117 \text{ sq.ft.}$$

Assuming a breeching with a rectangular section and with a ratio of sides of 2:1,

$$2D^2 = 117$$
$$D = 7.65 \text{ ft.} = \text{width}$$
and $2D = 15.3 \text{ ft.} = \text{height}$

Also $C_{br} = 45.9 \text{ ft.}$

The loss of draft through a rectangular breeching 7.65 ft. in width and 15.3 ft. in height is equal to:

$$h_{Br} = 0.0000893 \times 0.016 \times \frac{(133)^2 \times 1059.6 \times 100 \times 45.9}{(117)^3 \times 0.0855 \times 14.33} = 0.064 \text{ in. of water}$$

Loss of draft due to turns or bends. The gases make two right angled turns in passing from the boilers into the chimney: one when they leave the boiler and enter the breeching and the other when they leave the breeching and enter the chimney. The loss of draft due to a right angled turn is equal to:

$$h_T = 0.0000893 \times \frac{(133)^2 \times 1059.6}{(117)^2 \times 0.0855 \times 14.33}$$
$$= 0.10 \text{ in. of water}$$

The loss due to two such turns is equal to:

$$2 \times 0.10 = 0.20 \text{ in. of water}$$

Required draft. From the data and calculations, the required draft is equal to:

$$\begin{aligned} h_F &= 0.58 \text{ in. of water} \\ h_B &= 0.80 \text{ in. of water} \\ h_{Br} &= 0.064 \text{ in. of water} \\ h_T &= 0.20 \text{ in. of water} \\ \hline \text{Required draft} &= 1.644 \text{ in. of water} \end{aligned}$$

The loss due to velocity and the loss due to friction in the chimney are yet to be ascertained, but since both depend upon the diameter or area of the chimney, and the loss due to friction upon height of the chimney, neither one of which is known, not even approximately, at this stage of the calculations, it will be necessary to assume a trial value for each. However, it will be recalled that an arbitrary value was assumed for h_v in arriving at a value for the velocity of the chimney gases.

Hence $h_v = 0.10$ in. of water
Also assume $h_f = 0.10$ in. of water

Total loss of draft. The total trial loss of draft is equal to:

$$1.644 + 0.10 + 0.10 = 1.844 \text{ in. of water.}$$

This total trial loss of draft is equal to the theoretical draft of the chimney.

Theoretical draft per foot of chimney. For a chimney gas temperature of 600 deg. F., an outside air temperature of 60 deg. F., and a chimney gas density of 0.0855 lbs. per cu.ft. at 32 deg. F., the theoretical draft per foot of chimney at an elevation of 700 ft. above sea level is equal to:

$$K_D = 6.43 \times 14.33 \times \left(\frac{0.08071}{519.6} - \frac{0.0855}{1059.6}\right)$$
$$= 0.00687 \text{ in. of water}$$

Trial height of chimney. Finally the trial height of chimney is equal to:

$$H' = \frac{1.844}{0.00687} = 268 \text{ ft.}$$

Trial diameter. This trial height of 268 ft. is based on an assumed value of 0.10 in. of water for the loss of draft due to friction. Before attempting to check the accuracy of this assumption, it will be necessary to select a trial value for the diameter, or area, of the chimney. Assuming the same gas velocity as was used in determining the size of the breeching, 29.4 ft. per second,

$$A = \frac{133 \times 1059.6}{33.44 \times 29.4 \times 0.0855 \times 14.33}$$
$$= 117 \text{ sq.ft.}$$

Whence $D = 12.2$ ft.
and $C_d = 38.3$

Loss due to velocity. Using this area and diameter, the loss of draft due to velocity is equal to:

$$h_v = 0.0000893 \times \frac{(133)^2 \times 1059.6}{(117)^2 \times 0.0855 \times 14.33}$$
$$= 0.10 \text{ in. of water}$$

Loss due to friction (trial). The trial loss of draft due to friction is equal to:

$$0.0000893 \times 0.016 \times \frac{(133)^2 \times 1059.6 \times 248 \times 38.3}{(117)^3 \times 0.0855 \times 14.33}$$
$$= 0.13 \text{ in. of water}$$

The computed loss due to friction is slightly greater than the assumed value, hence, a correction is necessary.

Assume $h_f = 0.135$ in. of water

Then total draft equals:

$$1.644 + 0.10 + 0.135 = 1.879 \text{ in. of water}$$

$$H = \frac{1.879}{0.00687} = 273 \text{ ft., and } h_f =$$

$$0.0000893 \times 0.016 \times \frac{(133)^2 \times 1059.6 \times 253 \times 38.3}{(117)^3 \times 0.0855 \times 14.33}$$

$$= 0.135 \text{ in. of water}$$

Now since the assumed loss due to velocity and the assumed loss due to friction are both equal to the computed values, it follows that the total loss of draft throughout the installation is equal to the theoretical draft and the second trial height of chimney is equal to the required height. This required height, however, is dependent upon the accuracy of the assumed or trial diameter. As a general rule, the assumed trial diameter is always very close to the required diameter, if the former has been selected judiciously.

From the above example, it will be seen that it is necessary to use the cut-and-try process in determining the required height of chimney. Usually only one or two trials are necessary before the required height is found. The height of 273 ft. is correct if the assumed diameter and area are correct. Otherwise another trial must be made taking into consideration the proper diameter.

Required Diameter

Assuming that the required height of chimney, 273 ft., is correct, the diameter of the chimney is determined as follows:

$$V_t = 8.02\sqrt{273\left(\frac{0.944 \times 1059.6}{519.6} - 1\right)}$$

$$= 127.5 \text{ ft. per sec.}$$

Now $V_a = 29.4$

Then $R_c = \frac{29.4}{127.5} = 0.23$

$$K_{wc} = 268.2 \times 14.33 \times 0.0855 = 330$$

$$K_t = \sqrt{\frac{0.944 \times 1059.6 - 519.6}{(1059.6)^2 \times 519.6}}$$

$$= 0.0009076$$

Finally $D = \sqrt{\frac{133}{0.7854 \times 0.23 \times 330 \times 0.0009076 \times 16.5}}$

$$= 12.2 \text{ ft.}$$

Therefore the required size of chimney is 273 ft. in height and 12.1 ft. in diameter.

In addition to the various losses of draft noted heretofore, three other losses are encountered occasionally which will affect the size of a chimney to a considerable extent, viz.:

1. A right angled bend in the breeching,
2. An economizer in the breeching,
3. Sudden enlargement of an opening or an area.

Loss Due to Right Angled Bend in Breeching

In case there is a right angled bend in the breeching itself, there will be an additional loss of draft of 0.10 in. of water, the same as was determined for the other loss due to turns in the path of the gases. The various loss will be as follows:

$h_F = 0.58$ in. of water
$h_B = .80$ in. of water
$h_{Br} = .063$ in. of water
$h_T = .30$ in. of water
$h_v = .10$ in. of water
Assume $h_f = .143$ in. of water

$D_t = 1.986$ in. of water

Whence $H = \frac{1.986}{0.00687} = 289$ ft., and h_f

$$0.0000893 \times 0.016 \times \frac{(133)^2 \times 1059.6 \times 269 \times 38.3}{117)^3 \times 0.0855 \times 14.33}$$

$= 0.143$ in. of water

Loss through an Economizer

The loss through an economizer should always be obtained from the manufacturer of this piece of apparatus. Assume a condition where the maximum loss through an economizer is equal to 0.25 in. of water.

Then $h_F = 0.58$ in. of water
$h_B = .80$ in. of water
$h_{Br} = .063$ in. of water
$h_T = .20$ in. of water
$h_v = .10$ in. of water
$h_E = .25$ in. of water
Assume $h_f = .155$ in. of water

$D_t = 2.148$ in. of water

Whence $H = \frac{2.148}{0.00687} = 312$ ft.

and, as before, $h_f = 0.155$ in. of water

Loss Due to a Sudden Enlargement of an Opening or an Area

In the case of an extremely tall chimney with a relatively small diameter at the top, the internal cross-sectional area of the chimney at the level of the breeching opening is considerably larger than the minimum area of the chimney itself, or of the breeching. In such instances, there will be a loss of draft due to a sudden enlargement of an opening. This loss is given by the equation:

$$h_O = 0.10\ W_c\ P_o\ \frac{V^2_1 - V^2_f}{T_c}$$

Let it be assumed that the internal area of the chimney at the breeching entrance is equal to 206 sq.ft. Now the velocity of the gases as they leave the breeching, V_1, is equal to 29.4 feet per second as has already been determined. The velocity of the gases in the chimney at the breeching level, V_f, will be equal to:

$$V = \frac{133 \times 1059.6}{33.44 \times 206 \times 0.0855 \times 14.33} = 16.7 \text{ ft. per sec.}$$

$$\text{Then } h_O = 0.10 \times 0.0855 \times 14.33 \times \frac{(29.4)^2 - (16.7)^2}{1059.6}$$
$$= 0.068 \text{ in. of water}$$

$$\begin{aligned}
\text{Then}\quad h_F &= 0.58 \text{ in. of water}\\
h_B &= .80 \text{ in. of water}\\
h_{Br} &= .063 \text{ in. of water}\\
h_T &= .20 \text{ in. of water}\\
h_v &= .10 \text{ in. of water}\\
h_O &= .068 \text{ in. of water}\\
\text{Assume } h_f &= .141 \text{ in. of water}\\
\hline
D_t &= 1.952 \text{ in. of water}
\end{aligned}$$

$$\text{Then}\quad H = \frac{1.952}{0.00687} = 284 \text{ ft.}$$

and, as before, $h_f = 0.141$ in. of water

If, for example, all three of the above conditions were encountered in the same installation, the height of the chimney would be as follows:

Then $h_F = 0.58$ in. of water
$h_B = .80$ in. of water
$h_{Br} = .063$ in. of water
$h_T = .30$ in. of water
$h_E = .25$ in. of water
$h_O = .068$ in. of water
$h_v = .10$ in. of water
Assume $h_f = .170$ in. of water

$D_t = 2.331$ in. of water

$$\text{Whence } H = \frac{2.331}{0.00687} = 339 \text{ ft.}$$

and, as before, $h_f = 0.17$ in. of water

It has been assumed in the above examples that the diameter of the chimney remained constant regardless of the change in height. Considering the last example in which all of the conditions were included, the diameter is computed as follows:

Now $V_a = 29.4$ ft. per sec.

$$V_t = 8.02\sqrt{339\left(\frac{0.944 \times 1059.6}{519.6} - 1\right)}$$

$$= 142 \text{ ft. per sec.}$$

$$\text{Whence } R_c = \frac{29.4}{142} = 0.207$$

$K_{wc} = 330$

$K_t = 0.0009076$

$$\text{and} \qquad D = \sqrt{\frac{133}{0.7854 \times 0.207 \times 330 \times 0.0009076 \times 18.5}}$$

$$= 12.2 \text{ ft.}$$

Thus it will be seen that the diameter of the chimney is unaffected by a change in the height as long as the velocity of the chimney gases and the amount of gases flowing remains unchanged.

In arriving at the sizes of chimney as computed above, the working velocity of the chimney gases was assumed at 29.4 ft. per second, which in turn was based on a value of 0.10 in. of water for h_v. It is obvious that the value of V_a varies as h_v and that if a lower value had been assumed for h_v, the value of V_a would have been less, and vice versa. Using a different value for V_a will result in a chimney of a different size than the one computed. It is therefore apparent that a chimney of a certain and different size can be obtained for each different assumption for V_a. Now the question arises: is the size of chimney as determined for a velocity of 29.4 ft. per second the most economical in size?

CHAPTER XIV

ECONOMICAL VELOCITY

The various examples which have been worked out heretofore have been based on an arbitrarily selected chimney gas velocity of 29.4 ft. per sec. This velocity was based on a value of 0.10 inches of water for the loss of draft due to velocity. It is obvious that by assuming various values for the velocity of the chimney gases, correspondingly different sizes of chimney will result. For an assumed chimney gas velocity of 20.8 ft. per sec., for example, which corresponds to a value of 0.05 in. of water for h_v, a chimney 233 ft. in height and 14.3 ft. in diameter will be required. In other words, when 133 lbs. of gases are generated per sec. and it is required that these gases pass up the chimney at a velocity of 20.8 ft. per sec., a chimney 233 ft. in height will be required to help create sufficient draft to overcome all of the various losses of draft throughout the installation, and a diameter of 14.3 ft. will be required to pass these gases at the rate of 133 lbs. per sec., all under the restrictions originally imposed in the problem. Likewise, when the velocity of the chimney gases is assumed at 36 ft. per sec., which corresponds to a value of 0.15 in. of water for h_v, a chimney 320 ft. in height and 10.9 ft. in diameter will be required. Hence a chimney of a different combination of height and diameter is required for each different velocity assumed. Tables 16 and 17 give the required sizes of chimney for various assumed velocities and also the intermediate steps in arriving at the sizes. These results are shown graphically by Figs. 72 and 73.

Now the question arises: which of the various sizes given in the Tables is the most economical from the standpoint of price? The element of cost is, as a general rule, a relative issue, that is to say, there are many other factors which will affect the cost to a far greater extent than a combination of height and diameter. Degree of competition, proximity of building site to distributing centers and also railroads, materials of which the chimney is built, conditions to which the chimney will be subjected, and many other conditions, all have a greater effect on the cost than a relative combination of height and diameter. The above statements should be amplified to the extent that reasonable assumptions will be made in selecting the value for the working velocity. The size of a required chimney would never be based, for example, on an assumed chimney gas velocity of 10 ft. per sec., neither would a value of 40 ft. per sec. be used. The term "reasonable assumption" would include velocities between 25 and 35 ft. per sec.

However, leaving these factors out of consideration for the moment, it is quite apparent that the relative cost should vary as the diameter and also as the square of the height. This statement is proved by the fact that the cubical contents of the

TABLE 16

Ass'd h_v	V_a	A	C_{Br}	h_{Br}	h_T	h_F	h_B	h_v	Trial D	C_D	h_f	D_t	K_D	H	D_a	R_D
0.01	9.3	361	81	0.004	0.02	0.58	0.80	0.01	21.4	67.2	0.006	1.420	0.00687	207	1.404	0.990
.02	13.2	254	68	.009	.04	.58	.80	.02	18.0	56.5	.014	1.463	.00687	213	1.429	.977
.03	16.1	208	62	.014	.06	.58	.80	.03	16.3	51.3	.024	1.508	.00687	219	1.454	.964
.04	18.6	180	57	.020	.08	.58	.80	.04	15.1	47.5	.035	1.555	.00687	226	1.480	.952
.05	20.8	161	54	.027	.10	.58	.80	.05	14.3	44.9	.048	1.605	.00687	233	1.507	.939
.06	22.8	147	52	.034	.12	.58	.80	.06	13.7	43.0	.062	1.656	.00687	240	1.534	.926
.07	24.6	136	50	.041	.14	.58	.80	.07	13.2	41.4	.078	1.709	.00687	248	1.561	.913
.08	26.3	127	48	.048	.16	.58	.80	.08	12.7	39.9	.095	1.763	.00687	256	1.588	.901
.09	27.9	120	47	.056	.18	.58	.80	.09	12.4	38.9	.114	1.820	.00687	264	1.616	.888
.10	29.4	114	45	.064	.20	.58	.80	.10	12.1	38.0	.135	1.879	.00687	273	1.644	.875
.11	30.8	109	44	.072	.22	.58	.80	.11	11.8	37.0	.158	1.940	.00687	282	1.672	.862
.12	32.2	104	43	.081	.24	.58	.80	.12	11.5	36.1	.182	2.003	.00687	291	1.701	.849
.13	33.5	100	43	.089	.26	.58	.80	.13	11.3	35.5	.208	2.067	.00687	300	1.729	.837
.14	34.8	96	42	.097	.28	.58	.80	.14	11.1	34.8	.235	2.132	.00687	310	1.757	.824
.15	36.0	93	41	.105	.30	.58	.80	.15	10.9	34.2	.264	2.199	.00687	320	1.785	.812
.16	37.2	90	40	.114	.32	.58	.80	.16	10.7	33.6	.296	2.270	.00687	330	1.814	.799
.17	38.3	88	40	.123	.34	.58	.80	.17	10.6	33.1	.330	2.343	.00687	340	1.843	.786
.18	39.4	85	39	.132	.36	.58	.80	.18	10.4	32.8	.365	2.417	.00687	351	1.872	.774
.19	40.5	83	39	.142	.38	.58	.80	.19	10.3	32.2	.404	2.496	.00687	362	1.902	.762
.20	41.6	81	38	.151	.40	.58	.80	.20	10.2	31.9	.446	2.577	.00687	374	1.931	.750

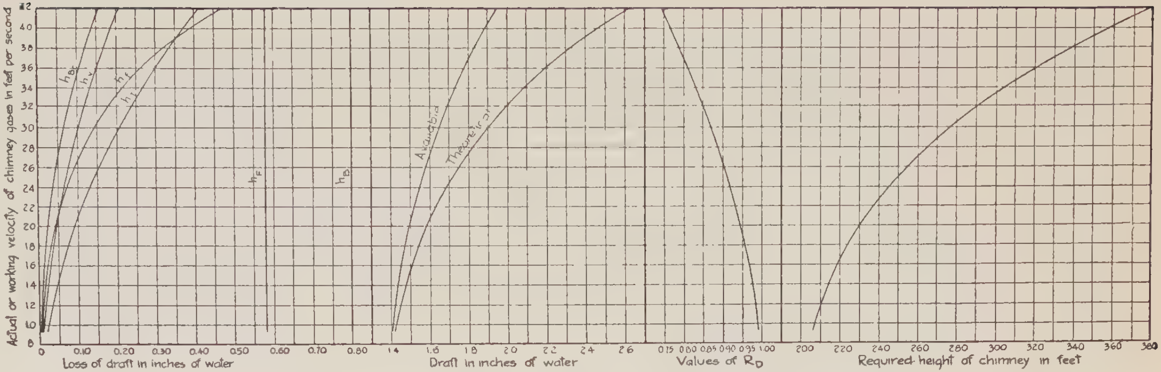

Fig. 72. Effect of chimney gas velocity on required height of chimney.

material of which the structure is built vary directly as the diameter and also directly as the square of the height. Thus the question of an economical velocity is brought up. Is there such a condition as an economical velocity? Is there a value for the velocity gases which will result in a combination of height and diameter that will result in a structure which will cost less than that of all other combinations?

From Tables 16 and 17, and Figs. 72 and 73, it will be seen that the various losses of draft vary directly as the square of the velocity of the chimney gases. Likewise, the theoretical draft (the sum of the various losses), the available draft and the height of the chimney vary in this same manner. From the standpoint of cost, then, insofar as the height of the chimney is concerned, it is best to keep the chimney gas velocity as low as possible. On the other hand, the diameter of the chimney varies inversely as the square root of the chimney gas velocity and insofar as the diameter of the chimney is concerned from a cost standpoint, it is best to have a high chimney gas velocity. The problem then is to select a velocity which will give a combination of height and diameter whose product will be least. Table 18 gives the products of height and diameter for the various chimney gas velocities noted. These results are shown graphically by Fig. 74. From these results, it will be seen that the product of diameter and height is least when the velocity of the chimney gases is approximately 26 ft. per sec. Under this theory then, of the various chimney sizes computed, that size with a product of height and diameter of 3250 which corresponds to a height of 256 ft. and a diameter of 12.7 ft., will be the least expensive, all other things either being equal or left out of consideration entirely. For this size, under the conditions originally imposed on it in the problem, the velocity of the chimney gases will be approximately 26 ft. per sec. and the loss of draft due to velocity will be approximately 0.08 in. of water. In short, for the conditions of this particular set of operating conditions, the relatively least expensive chimney will be had when the chimney gas velocity is assumed at approximately 26 ft. per sec.

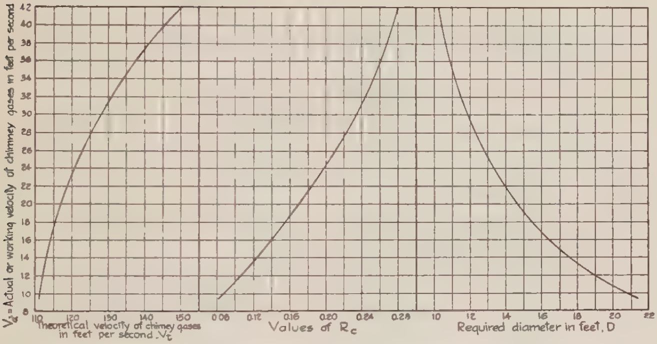

Fig. 73. Effect of Chimney Gas Velocity on Required Diameter of Chimney.

It is very apparent that it would be a tremendous task to work out several different combinations of height and diameter, such as has just been done, for a particular set of operating conditions in order to arrive at the relatively least expensive size. There should be some definite relation between V_a and H.D., and the conditions expressed in a problem, whereby this velocity may be found without undue effort. The problem, stated in a few words, is to determine an expression for V_a in terms of operating conditions which are either known definitely or can be ascertained, and which will give a minimum H.D. This relation will now be worked out in detail.

TABLE 17

V_a	V_t	R_c	K_{wc}	K_t	$\sqrt{H}$	D
9.3	111.0	0.084	337	0.0009076	14.4	21.4
13.2	112.6	.117	337	.0009076	14.6	18.0
16.1	114.3	.141	337	.0009076	14.8	16.3
18.6	116.0	.160	337	.0009076	15.1	15.1
20.8	117.8	.177	337	.0009076	15.3	14.3
22.8	119.6	.191	337	.0009076	15.5	13.7
24.6	121.5	.202	337	.0009076	15.8	13.2
26.3	123.4	.213	337	.0009076	16.0	12.7
27.9	125.4	.222	337	.0009076	16.3	12.4
29.4	127.4	.230	337	.0009076	16.5	12.1
30.9	129.4	.238	337	.0009076	16.8	11.8
32.2	131.5	.245	337	.0009076	17.1	11.5
33.5	133.6	.251	337	.0009076	17.3	11.3
34.8	135.7	.257	337	.0009076	17.6	11.1
36.0	137.9	.262	337	.0009076	17.9	10.9
37.2	140.1	.266	337	.0009076	18.2	10.7
38.4	142.3	.270	337	.0009076	18.5	10.6
39.5	144.5	.274	337	.0009076	18.8	10.4
40.5	146.8	.277	337	.0009076	19.1	10.3
41.6	149.2	.279	337	.0009076	19.4	10.2

$$\text{Now } H = \frac{D_t}{K_D} \qquad 268$$

$$= \frac{h_F + h_B + h_{Br} + h_T + h_v + h_f}{K_D} \qquad 269$$

TABLE 18

V_a	H	D	H × D
9.3	207	21.4	4430
13.2	213	18.0	3840
16.1	219	16.3	3570
18.6	226	15.1	3410
20.8	233	14.3	3330
22.8	240	13.7	3300
24.6	248	13.2	3270
26.3	256	12.7	3250
27.9	264	12.4	3270
29.4	273	12.1	3300
30.9	282	11.8	3330
32.2	291	11.5	3360
33.5	300	11.3	3390
34.8	310	11.1	3440
36.0	320	10.9	3490
37.2	330	10.7	3530
38.4	340	10.6	3590
39.5	351	10.4	3650
40.5	362	10.3	3730
41.6	374	10.2	3820

$$= \frac{h_F}{K_D} + \frac{h_B}{K_D} + \frac{h_{Br}}{K_D} + \frac{h_T}{K_D} + \frac{h_v}{K_D} + \frac{h_f}{K_D} \qquad 270$$

It will be seen from Table 16 and Fig. 72 that the various losses of draft, with the exception of the loss through the fuel bed and the loss through the boiler, vary as the square of the velocity of the gases. The losses through the fuel bed and the boiler remain constant regardless of the velocity of the gases after they leave the boiler. For the sake of convenience and simplicity, it will be assumed that the velocity of the gases in the breeching is the same as the velocity of the gases in the chimney, and also that the breeching has a circular section of the same area as the chimney.

Let $$\frac{h_F}{K_D} + \frac{h_B}{K_D} = \frac{h_F + h_B}{K_D} = K_a \tag{271}$$

Now $$\frac{h_T}{K_D} = \left(X_T \ \frac{0.10 W_c P_o}{K_D T_c} \right) V_a^2$$

$$= a_1 V_a^2 \tag{272}$$

in which $$a_1 = X_T \ \frac{0.10 W_c P_o}{K_D T_c} \tag{273}$$

Now $$\frac{h_v}{K_D} = \left(\frac{0.10 W_c P_o}{K_D T_c} \right) V_a^2$$

$$= a_2 V_a^2 \tag{274}$$

in which $$a_2 = \frac{0.10 W_c P_o}{K_D T_c} \tag{275}$$

Whence $$a_1 V_a^2 + a_2 V_a^2 = \frac{0.10 W_c P_o}{K_D T_c} \left(X_T + 1 \right) V_a^2$$

$$= K_b V_a^2 \tag{276}$$

in which $$K_b = \frac{0.10 W_c P_o}{K_D T_c} \left(X_T + 1 \right) \tag{277}$$

Now $$\frac{h_{Br}}{K_D} = \frac{0.10 f W_c P_o l}{K_D T_c} \cdot \frac{C}{A} V_a^2$$

For a circular section:

$$\frac{C}{A} = \frac{4}{D}$$

Whence $$\frac{h_{Br}}{K_D} = \left(\frac{0.40 f W_c P_o l}{K_D T_c} \right) \frac{V_a^2}{D}$$

$$= a_2 \frac{V_a^2}{D} \tag{278}$$

in which $a_3 = \frac{0.40fW_cP_ol}{K_DT_c}$ 279

Now $\frac{h_f}{K_D} = \left(\frac{0.40fW_cP_o}{K_DT_c}\right) \frac{L}{D} V_a^2$

$= a_4 \frac{H}{D} V_a^2$ 280

in which $a_4 = \frac{0.40fW_cP_o}{K_DT_c}$ 281

In equation 280, it has been assumed that $L = H$.

From equations 270, 271, 276, 278, and 280:

$$H = K_a + K_bV_a^2 + a_3 \frac{V_a^2}{D} + a_4 \frac{H}{D} V_a^2$$

Clearing of fractions:

$$HD = DK_a + DK_bV_a^2 + a_3V_a^2 + Ha_4V_a^2$$

$$HD - Ha_4V_a^2 = DK_a + DK_bV_a^2 + a_3V_a^2$$

Whence $H = \frac{DK_a + DK_bV_a^2 + a_3V_a^2}{D - a_4V_a^2}$ 282

Now $D = 0.195 \sqrt{\frac{W_aT_c}{V_a W_c P_o}}$

$= 0.195 \sqrt{\frac{W_aT_c}{W_c P_o}} \sqrt{\frac{1}{V_a}} = \frac{m}{V_a^{1/2}}$ 283

in which $m = 0.195 \sqrt{\frac{W_aT_c}{W_c P_o}}$ 284

Substituting in equation 282 the expression for D as given by equation 283:

$$H = \frac{\left(\frac{m}{V_a^{1/2}}\right) K_a + \left(\frac{m}{V_a^{1/2}}\right) K_b V_a^2 + a_3 V_a^2}{\frac{m}{V_a^{1/2}} - a_4 V_a^2}$$

$$= \frac{mK_a + mK_b V_a^2 + a_3 V_a^{5/2}}{m - a_4 V_a^{5/2}}$$

Finally, from equations 282 and 283:

$$HD = \frac{mK_a + mK_b V_a^2 + a_3 V_a^{5/2}}{m - a_4 V_a^{5/2}} \times \frac{m}{V_a^{1/2}}$$

$$= \frac{m^2K_a + m^2K_b V_a^2 + ma_3 V_a^{5/2}}{mV_a^{1/2} - a_4 V_a^3} \qquad 285$$

Equation 285 gives the value of HD in terms of V_a and several constants, the values of which may easily be found. An inspection of Table 18 and also Fig. 74 will disclose the fact that HD is a minimum for a certain value of V_a. This value of V_a may be found by differentiating the expression for H D with respect to V_a and then placing the resulting equation equal to zero.

The differential of a fraction is equal to the denominator times the differential of the numerator minus the numerator times the differential of the denominator, all over the square of the denominator. The differential of a sum is equal to the sum of the differentials.

For convenience let $m^2K_a = A$
$m^2K_b = B$
$ma_3 = C$
$m = D$
$a_4 = E$

Then $HD = \dfrac{A + BV_a^2 + CV_a^{5/2}}{DV_a^{1/2} - EV_a^3}$

Whence $\frac{d\,(HD)}{dV_a} = \frac{(DV_a^{1/2} - EV_a^3)\left(2BV_a + \frac{5}{2}\;CV_a^{3/2}\right) - (A + BV_a^2 + CV_a^{5/2})\left(\frac{1}{2}DV_a^{-\frac{1}{2}} - 3EV_a^2\right)}{(DV_a^{1/2} - EV_a^3)^2}$

Rationalizing the numerator:

$$\left(2BDV_a^{3/2} + \frac{5}{2}CDV_a^2 - 2BEV_a^4 - \frac{5}{2}\;CEV_a^{9/2}\right)$$

$$-\left(\frac{1}{2}ADV_a^{\;-1/2} - 3AEV_a^2 + \frac{1}{2}BDV_a^{3/2} - 3BEV_a^4 + \frac{1}{2}CDV_a^2 - 3CEV_a^{9/2}\right)$$

$$= \frac{3}{2}BDV_a^{3/2} + 2CDV_a^2 + BEV_a^4 + \frac{1}{2}CEV_a^{9/2} - \frac{1}{2}ADV_a{-}^{1/2} + 3AEV_a^2$$

Substituting the proper quantities for A, B, C, D, and E:

$$\frac{3}{2}\,m^3K_bV_a^{3/2} + 2m^2a_3V_a^2 + m^2a_4K_bV_a^4 + \frac{1}{2}\,ma_3a_4V_a^{9/2} - \frac{1}{2}\,m^3K_aV_a^{\;-1/2} + 3m^2a_4K_aV_a^2$$

Clearing of fractions and factoring out $mV_a^{3/2}$:

$$3m^2K_b + 4ma_3V_a^{1/2} + 2ma_4K_bV_a^{5/2} + a_3a_4V_a^3 - m^2K_aV_a{-}^{2} + 6ma_4K_aV_a^{1/2}$$

Finally: $\frac{d\,(HD)}{dV_a} = \frac{3m^2K_b + 4ma_3V_a^{1/2} + 2ma_4K_bV_a^{5/2} + a_3a_4V_a^3 - m^2K_aV_a^{-2} + 6ma_4K_aV_a^{1/2}}{(mV_a^{1/2} - a_4V_a^3)^2}$

Now H D is a minimum when $\frac{d\,(HD)}{dV_a} = 0$

Therefore: $\frac{3m^2K_b + 4ma_3V_a^{1/2} + 2ma_4K_bV_a^{5/2} + a_3a_4V_a^3 - m^2K_aV_a^{\;-2} + 6ma_4V_a^{1/2}}{(mV_a^{1/2} - a_4V_a^3)^2} = 0$

Clearing of fractions will remove the denominator. Now by factoring out m in the numerator and re-arranging:

$$V_a^2 \left(3mK_b + 4a_3V_a^{1/2} + 2a_4K_bV_a^{5/2} + \frac{a_3a_4}{m}V_a^3 + 6a_4K_aV_a^{1/2}\right) = mK_a \qquad 286$$

The terms

$$2a_4K_bV_a^{5/2} \text{ and } \frac{a_3a_4}{m}V_a^3$$

will always be relatively small and for all practical purposes may be disregarded entirely.

Whence $V_a^2\,(3mK_b + 4a_3V_a^{1/2} + 6a_4K_aV_a^{1/2}) = mK_a$

The above equation cannot be solved for V_a except by the method of successive approximation. However, V_a will vary between 20 and 40 with a fair average of 30 ft. per sec. The two terms inside the parenthesis containing the factor $V_a^{1/2}$ may therefore be rationalized by substituting

$$(30)^{1/2} = 5.5 \text{ for } V_a^{1/2}$$

This substitution will not affect the accuracy of the final equation for V_a for all practical purposes.

Whence $V_a^2\,(3mK_b + 22a_3 + 33a_4K_a) = mK_a$

And finally $V_a = \sqrt{\dfrac{mK_a}{3mK_b + 22a_3 + 33a_4K_a}}$ 287

Now from equation 277:

$$K_b = \frac{0.10W_cP_o}{K_DT_c}\,(X_T + 1)$$

Assuming $W_c = 0.0855$

and $P_o = 14.7$

$$K_b = \frac{0.125\ (X_T + 1)}{K_D T_c} \tag{288}$$

Likewise, from equation 279:

$$a_3 = \frac{0.40 f W_c P_o l}{K_D T_c}$$

Assuming $f = 0.016$

$W_c = 0.0855$

and $P_o = 14.7$

$$a_3 = \frac{0.008l}{K_D T_c} \tag{289}$$

And finally from equation 281:

$$a_4 = \frac{0.40 f W_c P_o}{K_D T_c}$$

Assuming $f = 0.016$

$W_c = 0.0855$

and $P_o = 14.7$

$$a_4 = \frac{0.008}{K_D T_c} \tag{290}$$

Substituting these simplified expressions for K_b, a_3, and a_4 in equation 287:

$$V_a = \sqrt{\frac{mK_a K_D T_c}{0.375m\ (X_T + 1) + 0.176l + 0.284K_a}} \tag{291}$$

Equation 291 gives in the simplest possible form the value of V_a which will result in a minimum value for H D for any selected or arbitrarily chosen set of operating conditions. The derivation of this

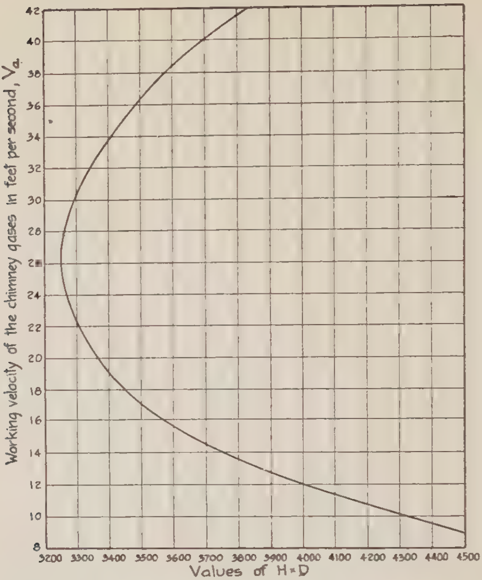

Fig. 74. Typical Relation of Velocity of Chimney Gases to Product of Height and Diameter, Illustrating Velocity for Most Economical Size of Chimney.

equation has been carried out in detail because of its great importance in chimney design, not only for the values which it gives but also for the tremendous amount of time it saves. This equation as it stands is not correct in the strict mathematical sense of the term due to the fact that two minor terms have been disregarded and also an arbitrary assumption has been made for a certain factor. The error introduced by disregarding the two terms and approximating a factor in two terms, however, will not amount to more than one per cent and for this reason the equation may be considered sufficiently accurate for all practical purposes. The equation is also based on an assumed value of 0.016 for f, 0.0855 for W_c, and 14.7 for P_o. Except in extreme cases, these assumed values will not materially affect the correctness of the true value of V_a. For extremely high altitudes, the proper value for P_o should be used and the value of V_a then computed from equation 287. It was also assumed that the breeching was circular in section and that the velocity of the gases in the breeching was the same as that of the velocity of the chimney gases. These two assumptions are seldom true, but again the error introduced will be practically negligible. It was necessary to make the above noted assumptions, otherwise it would have been impossible to have derived a rational equation for V_a.

The value of V_a which will give a minimum H D for the operating conditions assumed for the typical example in the last chapter is computed as follows:

$$m = 0.195 \sqrt{\frac{W_a T_c}{W_c P_o}} = 0.195 \sqrt{\frac{133 \times 1059.6}{0.0855 \times 14.33}} = 66$$

$$K_a = \frac{h_F + h_B}{K_D} = \frac{0.58 + 0.80}{0.00687} = 200$$

$K_D = 0.00687$ as determined heretofore

$T_c = 1059.6$

$X_T = 2$

$l = 100$

Substituting these values in equation 291:

$$V_a = \sqrt{\frac{66 \times 200 \times 0.00687 \times 1059.6}{0.375 \times 66 \times 3 + 0.176 \times 100 + 0.284 \times 200}}$$

$$= \sqrt{\frac{95{,}250}{148}}$$

$$= \sqrt{644}$$

$$= 25.4 \text{ ft. per sec.}$$

If this value is corrected for $P_o = 14.33$ and a closer approximation for $V_a^{1/2}$

$$V_a = \sqrt{\frac{66 \times 200 + 0.00687 \times 1059.6}{0.366 \times 66 \times 3 + 0.159 \times 100 + 0.238 \times 200}}$$

$= 26.5$ ft. per sec. which practically agrees with the value given by Table 24.

It so happens that the arbitrarily chosen loss of draft due to velocity of 0.10 in. of water which resulted a chimney gas velocity of 29.4 ft. per sec. did not result in the most economical size of chimney. Had the loss due to velocity been assumed at 0.08 in. of water instead, the chimney gas velocity would have been approximately 26 ft. per sec. and the most economical size would then have been determined. In actual practice, the economical velocity is first determined from the conditions assumed and the loss due to velocity computed from this value. The operations for determining the proper size are then carried on as was done in the example under discussion. The required size then is 256 ft. in height and 12.7 ft. in diameter.

Equation 291 is a tremendously important equation both as to the result it gives and also as to the great amount of time it saves. It is in reality the primary equation in determining the size of a new or contemplated chimney. It forms the connecting link between height and diameter. After the proper values have been substituted in this equation and the value for V_a determined, there will be one and only one size of chimney which will answer the purpose. This is a fact which the writer has continually been attempting to establish, namely: that for any one set of operating conditions, there is one and only one size of chimney which will satisfy all conditions. The development of this equation proves this fact beyond a doubt.

In the discussion hitherto, it has been assumed that the draft necessary to overcome all of the various losses is supplied by the aid of a chimney alone. Both the height and diameter have been designed to accommodate the installation when it is operating under maximum conditions, or maximum load. However, when the plant is operating under normal conditions, or load, both the height and diameter of the chimney are too large. Too much draft is then created and it is necessary to partially close the damper. This results in increased damper friction and also in throttling the gases, thereby increasing the friction and, as a result, the loss of draft due to friction. This extra height and diameter of chimney over that required for normal operating conditions involves considerable of an investment upon which the dividends are very small indeed. This fact is often converted to the disadvantage of the chimney as a sole draft producer in a plant by the exponents of other more efficient arrangements.

The majority of the larger and more up-to-date plants of the present day operate under a combined fan and chimney arrangement, as far as draft is concerned. In such a system, a fan is used to produce the static head, or draft, necessary to overcome the loss through the fuel bed and a chimney to produce the draft necessary to overcome the resistances throughout the remainder of the installation. The draft in the combustion chamber is arbitrarily kept at from 0.10 to 0.15 in. of water. This system results in a considerably shorter chimney, of course, but on the other hand a fan and driving arrangement is required and the cost of this may not be offset by the saving in the shorter chimney. However, the fan scheme permits of better and more ease of control and is more efficient, perhaps, in the long run.

In the example under discussion, let it be assumed that a fan will produce the draft necessary to overcome the loss of draft through the fuel bed and that the draft over the fire, or in the combustion chamber, will be 0.15 in. of water. Determine the required height of chimney for these conditions:

$h_F = 0.15$ in. of water
$h_B = .80$ in. of water
$h_{Br} = .063$ in. of water
$h_T = .20$ in. of water
$h_v = .10$ in. of water

Assume $h_f = \underline{.10}$ in. of water

$D_t = 1.413$ in. of water

Whence $H = \frac{1.413}{0.00687} = 206$ ft.

and

$$h_v = 0.0000893 \times 0.016 \times \frac{(133)^2 \times 1059.6 \times 186 \times 38.3}{(117)^3 \times 0.0855 \times 14.33}$$

$$= 0.10 \text{ in. of water}$$

Therefore, the required height is 206 ft. as compared with 273 ft. when the chimney is used to create all the draft, a saving of 67 ft. in height. The diameter will remain the same.

Extremely high chimneys, 250 ft. and over, run into considerable amounts of money. They also require considerable space which is usually at a premium around a large plant. Oftentimes it is necessary to place the chimney at the end of a long row of boilers and in this case an extremely long breeching is required. This in turn adds to the loss of draft and increases the required height as a result. Again, in central station plants, the boilers in addition to being set high, are mounted in the second story of the building. In case the chimney is located outside the building, it may be necessary to add from 20 to 30 ft. to the required height in order to reach the ground. This procedure may result in an extremely tall chimney with its consequent disproportionate cost. In such arrangements, it is the usual custom to place the chimney, or chimneys, on top of the building and support them by means of a platform on top of structural framework. This results in a considerably shorter chimney and simplifies the breeching arrangement. The breeching, or breechings, may enter the chimney at the bottom and through the platform, or at the side and directly above the platform.

Determining the required size of a chimney for a proposed installation is a problem which merits as much, if not more, consideration as that of any other factor or part of the plant. For some unaccountable reason the size of most chimneys has, in the past, been selected from a table based on the horsepower of the boilers. This practice is very dangerous. More likely than not, the wrong size will be selected. There are so many factors that enter into the required size that no table or set of curves can possibly include all of them. Equations which have been deduced for specific cases should not be used generally and indiscriminately.

Summarizing in a few words, the required size of a chimney should be determined as follows: Base the required height on the sum of the various losses of draft encountered throughout the installation, and the diameter upon the amount of gases flowing. Use care in selecting the values which represent the maximum operating conditions. The greatest height and maximum diameter will be required to properly serve the plant during maximum operation. At other times the draft can be controlled by the damper. Use care in selecting proper values for average operating conditions, such as the temperature of the outside air, the density of the chimney gases, etc. Base the temperature of the chimney gases upon the lowest value which will ever be encountered, remembering that economizers decrease the chimney gas temperature to a fairly low degree. See that breechings are properly designed and are at least as large in area as the chimney itself.

A chimney, the size of which has been properly designed, will prove to be an enormous asset to a plant. A plant which is operating with a properly designed chimney has every reason to show a high efficiency.

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